Center for Energy Efficient
Electronics Science

Draft

Period 9 Annual Report

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Berkeley UNIVERSITY OF CALIFORNIA
Massachusetts Institute of Technology
STANFORD UNIVERSITY
THE UNIVERSITY OF TEXAS AT EL PASO
FLORIDA INTERNATIONAL UNIVERSITY
CALIFORNIA COMMUNITY COLLEGES CHANCELLOR'S OFFICE

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I. GENERAL INFORMATION

1a. Center Information

Date submitted	November 30, 2018
Reporting period	March 1, 2018– February 28, 2019
Name of the Center	Center for Energy Efficient Electronics Science (E^3S)
Name of the Center Director	Eli Yablonovitch
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Participating Institutions

Below are the names of participating institutions, their roles, and (for each institution) the name of the contact person and their contact information at that institution.

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Role of Institution at Center	MIT is a lead research, education, and outreach partner.

Institution Name	Stanford University Shan Xiang Wang
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Role of Institution at Center	Stanford is a lead research, education, and outreach partner.

Institution Name	The University of Texas at El Paso (UTEP) David Zubia
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Role of Institution at Center	UTEP is a research, education, and outreach partner to encourage greater minority participation in engineering.

Institution Name	Florida International University (FIU) Sakhrat Khizroev
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Role of Institution at Center	FIU is a research, education, and outreach partner to encourage greater minority participation in engineering.

Institution Name	California Community Colleges Chancellor's Office Pamela D. Walker
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Role of Institution at Center	California Community Colleges Chancellor's Office represents the California Community College system whose multiple member campuses are education and outreach partners to encourage greater women, minority and first generation college student participation in science, engineer and mathematics.

1b. *Biographical Information of New Faculty*

Please see Appendix A for biographical information of three new faculty members. One of the new members (Shan Wang) joined the Center on September 1, 2018 while the other two new members (Jeehwan Kim and Farnaz Niroui) will formally join the Center with the start of period 10.

1c. *Primary Contact Person*

Below is the name and contact information for the primary person to contact with any questions regarding this report.

Name of the Individual	Michael Bartl
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2. *Context Statement*

Established in 2010, the Center for Energy Efficient Electronics Science (E^3S) is a Science and Technology Center funded by the U.S. National Science Foundation. The overarching goal of the Center for E^3S is to revolutionize information processing by developing next-generation electronic systems approaching the theoretical limits of energy efficiency in logic switching. This goal is pursued through a multi-faceted approach, including research, education, diversity, outreach and knowledge transfer activities. At the heart of the Center's activities lies the education of a diverse generation of scientists and engineers to be the future leaders, researchers, educators, and technicians in electronics and information technology. The Center for E^3S envisions a legacy promoting the application of its research and education outcomes as foundation for future ultralow-energy logic systems.

Central to the Center's research and education mission is a collaborative approach, involving engineers, chemists, physicists, and materials scientists from five top universities to establish the science and fundamental knowledge needed for developing highly energy-efficient logic switches. The five partner universities comprising E^3S are the University of California, Berkeley (*Berkeley*), Massachusetts Institute of Technology (*MIT*), Stanford University (*Stanford*), University of Texas at El-Paso (*UTEP*), and Florida International University (*FIU*). These five core institutions are supported by industry-leading companies, including Applied Materials, IBM, Intel Corporation, HP Enterprise, and Lam Research. In addition, the Center for E^3S has established strong ties with the California Community College System to provide educational outreach and train the next generation of researchers in low-energy electronics.

Entering its ninth year, the Center's research goal of replacing the conventional transistor with ultralow-power switches is now as relevant as ever. Recent advancements in cloud computing, social networking, mobile internet and data analytics, and the associated increase of battery powered electronic systems, have made development of logic switches that can operate at significantly reduced power consumption inevitable. The need for energy-efficient logic systems is further driven by increasing importance of wireless sensor swarms, body-centered networks, data centers and servers, and supercomputers. While conventional transistors were the key for forging this revolution in an interconnected society, conventional thermally activated conduction represents a serious drawback since powering voltages of ~0.7 volts are required to provide a good ON/OFF current ratio, even as transistors have become smaller.

At the most fundamental level, today's energy used to manipulate a single bit of information is orders of multitude times higher than theoretical limits. For example, the wires connecting the transistor could operate with a very good signal-to-noise ratio at voltages <8 mV. Since power consumption is proportional to the square of operating voltage, the energy currently used to manipulate a single bit of information is four orders of magnitude greater than needed. For example, four orders of magnitude is equivalent to the difference of charging a cell phone once a day, or once every 30 years! As the energy in current data processing is related to charging and discharging the communication wires of conventional chips, additional power-savings can be achieved by pursuing an optical communication strategy and replacing some longer metal interconnects with optical waveguides. Therefore, a more sensitive, lower-voltage switch providing energy-efficient on-chip communication interconnects are needed as successor to conventional technologies.

The Center for E^3S was formed nine years ago to address these very challenges and respond to the critical need for fundamental and conceptual breakthroughs in the underlying physics, chemistry, materials science and device engineering. Since then, E^3S has made significant contributions in the development of next-generation ultralow energy switching concepts. This was achieved by identifying barriers, revolutionary concepts and scientific principles that would enable transformative and fundamentally new digital-information processing science.

The Center recognized early on that new, ultra-low energy logic systems must meet a set of key specifications to be of practical use.

The three most important requirements for the logic switch are:

- Steepness (or sensitivity): ~1 mV/decade; to enable a switching swing of only a few milli-Volts
- ON/OFF conductance ratio: ~10^6-10^4:1; to achieve low leakage current in the OFF-state (since logic switches are often at rest waiting for a signal.)
- Current density or conductance density (for miniaturization): ~1 mS/μm; required for fast charging of interconnect wires within the clock-period. (Since the goal of the new switch is to lower the voltage well below 1 V, the corresponding switch conductance requirement becomes 1mS/μm rather than the more conventionally given requirement of 1mA/μm.)

The requirements for ultralow energy optical communication are:

- Replace longer metal interconnects with silicon optical waveguides
- Approach the quantum limit of 2.5aJ/bit or 20 photons/bit as the lowest energy per bit (although 200 photons/bit would already be a major breakthrough)

Strategic Research Plan & Rationale

From its inception, the Center for E^{3}S has conducted research in four distinct but interrelated themes: (I) Nanoelectronics: solid-state millivolt switching; (II) Nanomechanics: zero-leakage switching; (III) Nanophotonics: few-photon optical communication; (IV) Nanomagnetics: low-energy, fast magnetic switching. Overarching these four research themes is Systems Integration to ensure that the component research outcomes of the Center will be effective in enabling future ultra-low energy information systems. Themes I, II and IV pursue different approaches to ultralow-energy electrical switching, while theme III addresses short range optical communication, particularly intra-chip.

In 2015, at the beginning of the Center's second five years, PI and Center Director, **Eli Yablonovitch** led the Center's members (faculty, postdocs, students, and staff) to review the accomplishments and challenges of the first five years and plan strategically for the Center to continue building a legacy in the coming years. Out of the discussions and sharing of perspectives, the Center has formed the E^{3}S Strategic Plan (2015-2020), which included, for example a re-direction of the tunnel transistor work away from the conventional group IV & III-V materials to the newer semiconductors. In period 9, we have continued with the new Strategic Research Plan, including the Center's research theme strategies and approaches, which are outlined below.

Theme I: Nanoelectronics

The goal of the nanoelectronics theme has been to develop a semiconductor switch sensitive enough to be actuated around 10mV, orders of magnitude more energy efficient than conventional transistors. Led by **Eli Yablonovitch** (*Berkeley*), the nanoelectronics team combines engineers, physicists and chemists from Berkeley and MIT focused on understanding mechanisms and device physics of low-energy switching, searching for new semiconductor materials, and developing new switching device concepts. Among possible alternative switching mechanisms, the tunnel mechanism appears to be inevitable since, tunneling is an unavoidable physical effect at the nanoscale. Whereas theoretical predictions promise excellent steepness, ON/OFF ratios and conductance for tunnel transistors [1], experimental results so far are rather disappointing. As has been emphasized by E^{3}S researchers [2, 3], the reason for the disappointing tunnel characteristics in current state-of-the-art devices is that they operate on the tunnel distance modulation mechanism, and not in the more desirable density-of-states modulation mechanism. While tunnel distance modulation is steep at low currents [4-7], these devices are rather insensitive at the high conductance (current) densities needed for acceptable clock speed. Averaged over both low and high current densities, a ~50 percent reduction in operating voltage might be achievable with tunnel distance modulation.

In contrast, the density-of-states modulation mechanism, which is also called the energy filtering mechanism, projects high conductance in the ON-state. Since only the energy filtering mechanism can achieve order-of-magnitude reductions of the operating voltage, E^3S has focused on elucidating the underlying tunnel device physics—as opposed to moderate device optimization being pursued by industry—and recognized early materials interface perfection higher than ever previously achieved in solid-state electronics is needed. Consequently, a significant portion of the research effort in the E^3S nanoelectronics theme has focused on identifying, synthesizing and incorporating new materials that promise excellent surface and interface properties and low defect densities.

In period 9, the nanoelectronics theme has continued research efforts toward 1) gaining in-depth understanding of interfacial effects and trap-assisted tunneling, and 2) developing new material systems with ultra-low interfacial defect density. The model system used in the Center for studying interfacial effects, trap-assisted tunneling, and other non-idealities of tunnel transistors are vertical nanowire tunnel transistor structures fabricated in the **del Alamo** group (*MIT*). Current experimental goals are to optimize fabrication of sub-10 nm vertical nanowire III-V TFET devices displaying single-channel properties and individual defect states. Current-voltage spectroscopy results of single trap nanowire tunneling is being conducted to discover the ultimate performance potential of tunnel transistors. **Yablonovitch** is addressing the question of the fundamental spectroscopic sharpness of tunneling energy levels, with the emphasis on the spectral wings, which determine ON/OFF ratio.

In recent years, the search for new material systems with ultra-low interfacial defect states has become the dominating research effort of the nanoelectronics theme. The goal remains to be the first group to demonstrate tunnel transistors truly operating in the density-of-state switching modulation mechanism with high ON/OFF ratios and steep modulation, even at high conductance (current) densities. To achieve this goal, the nanoelectronics theme has identified two promising materials systems as potentially low-defect density semiconductors: two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs). The 2D-TMDC research is a collaborative effort between the groups of **Ali Javey** and **Eli Yablonovitch** (both *Berkeley*) and **Jing Kong** (*MIT*). The current goals are to develop new bottom-up synthesis methods based on MOCVD, to study defect physics and properties of these new semiconductors, and to integrate low defect-density 2D chalcogenides into tunnel device structures. The goals of the Center's GNR project have been the design and synthesis of quantum tunneling structures with built-in molecular quantum dots, incorporation of dopant atoms, and synthesis of metallic nanoribbons to serve as conductive leads. Experimental efforts by organic chemist **Felix Fischer** are supported by physicist, **Steven Louie** (*Berkeley*), with first principles quantum mechanical calculations, and **Eli Yablonovitch** and **Jeffrey Bokor** (*Berkeley*) by providing device fabrication guidance.

Theme II: Nanomechanics

The nanomechanics theme develops low-voltage switches based on electromechanical relays as ultra-low energy alternatives to the current-day transistor. Led by **Tsu-Jae King Liu** (*Berkeley*), the goal of the nanomechanics theme has been to demonstrate reliable nano-electromechanical (NEM) switch operation at or below 10 mV. In addition, guided by the Center's system integration team, strategies have been investigated to apply zero-leakage NEM-based switching in a system application. The nanomechanics research theme takes advantage of the very low OFF-state leakage (I_{OFF}) and abrupt switching behavior of mechanical switches across a wide range of temperatures [8]. While, in principle, NEM-based switches can be operated at much lower voltage than current transistors, surface adhesion ultimately limits relay scaling. In response, the nanomechanics theme has focused on new approaches that go beyond voltage reduction through scaling and new device design. In fact, E^3S nanomechanics researchers pursue the concept of a tunneling relay whereby the electrical activation will occur when the two electrodes are brought into close proximity, but do not touch each other. The spacing of the electrodes can be controlled by non-pull-in-mode operation and by compressible molecular spacers. The latter approach constitutes a molecular squeeze-switch, or "Squitch" [9]. In addition, the theme has developed the "Stritch" concept (short for stretch-switch), a piezoresistive NEM switch by straining 2D chalcogenide layers using electromechanical actuators.

In period 9, the goals of the nanomechanics research efforts have focused on further lowering the contact adhesion energy of electromechanical switches and demonstration of NEM relay-based integrated circuits operating below 100 mV, optimization of the squitch device fabrication process, and development of new stritch design. The groups of **Tsu-Jae King Liu** and **Junqiao Wu** (both *Berkeley*) have continued to investigate minimization of hysteresis voltage of NEM switches by implementing a new relay structure (2-contact design) and using branched molecules as anti-stiction electrode coatings to achieve devices with sub-10 mV hysteresis voltage.

The squitch concept, which is pursued by the groups of **Jeffrey Lang**, **Vladimir Bulovic** and **Timothy Swager** (all at *MIT*), consists of a vertically-movable source supported by a molecular monolayer that is compressed upon application of a gate-source voltage, thereby permitting source-drain electron tunneling. The research goal in this period has been to optimize each step in the fabrication process and increase the yield of functioning devices. The third electromechanical switching concept developed and investigated in the nanomechanics theme is the stritch device, a joint project between **David Zubia** (*UTEP*) and the **Liu**, **Wu** and **Javey** groups (all *Berkeley*). In this device, the stretching of the semiconductor chalcogenide material by electromechanical actuators causes straining of a 2D chalcogenide layer. This results in tensile strain and concomitant change in the chalcogenide bandgap and conductivity. The current goals of this project focus on the actuator re-design to enable stretching of the 2D monolayers by more than 3%.

Theme III: Nanophotonics

The nanophotonics theme pursues solutions for on-chip optical communication between electronic switches at unprecedented efficiency levels. In fact, led by **Ming Wu** (*Berkeley*), the goal of E^{3}S nanophotonics researchers is to approach experimentally the quantum limit in a data-link: from currently used ~20,000 photons per bit to just a few hundreds of photons per bit or less. As most of the energy in current data processing is related to charging and discharging the communication wires of conventional chips, the aim of the nanophotonics theme has been to replace conventional wires with optical waveguides, such as silicon photonics. To meet this goal, research in the E^{3}S nanophotonics theme is focused on the development of ultra-efficient and sensitive optical components (both at the emitter and receiver side). Furthermore, these components need to be integrated with waveguides and miniaturized to be comparable to the size of transistors. E^{3}S circuits and systems analysis revealed an important conflict in photreceiver design: While the photodetector needs be of sufficient size to absorb the photons, the short-transit-time, high-speed pre-amplifier must be ultra-small [10]. As a result, the photo-transistor research in the Center, which tried to combine both functions into a single device, had been eliminated at the end of period 7. On the photoemitter side, E^{3}S has introduced the antenna-enhanced nanoLED concept with the goal to be faster and more energy efficient than the stimulated emission of lasers, which are currently the ubiquitous light source in optical communications [11].

In period 9, the groups of **Ming Wu**, **Eli Yablonovitch** and **Connie Chang-Hasnain** (all *Berkeley*), and **Eugene Fitzgerald** and **Jeehwan Kim** (*MIT*) have continued to optimize design and properties of antenna enhanced nanoLEDs and to develop efficient coupling of nanoLED emission into single mode optical waveguides. The concept of the antenna enhanced nanoLED was invented and developed in the Center for E^{3}S with the goal to be faster and more energy efficient than the stimulated emission of lasers. The goals in this period have been to perform time-resolved photoluminescence studies of the spontaneous emission lifetime of the III-V antenna-LED, increase the electroluminescence quantum efficiencies of chalcogenide nanoLEDs, and use of inverse design concepts to optimize the total waveguide-coupled external quantum efficiency.

At the systems level, the **Wu**, **Stojanović**, and **Yablonovitch** groups teamed up to simulate a full digital-to-digital optical link with inclusion of the receiver. Reasonable values were assumed for the photodiode

[12], and the CMOS receiver's extrinsic current-unity gain. The receiver model considers not only resistor thermal noise and transistor FET noise, but also the input swing sensitivity required to have an output rail-to-rail signal. All of these metrics combine to yield a topology and data-rate specific energy-per-bit (E/b) both for the receiver side and transmitter side. For each data-rate, an optimization was performed to find the minimum E/b sweeping over the number of linear amplifiers, the number of interleaves, and the FET sizing.

Theme IV: Nanomagnetics

The nanomagnetics theme focuses on developing current-driven magnetic elements for electrical communication with switching energies at the atto-Joule level and ultrafast switching speeds (below 10 picoseconds). To achieve this, the E^{3}S team, led by **Jeffrey Bokor** (*Berkeley*), takes advantage of spin-transfer torque magnetic tunneling junctions and newly discovered ultra-sensitive current driven switches employing spin-orbit torque (spin-Hall effect) to switch a magnet [13]. Such a component can have current in/current out gain, as well as fan-out. Since the constituents tend to be metallic, the voltage requirement is low, compatible with the goal of low dynamic power as the digital circuits switch. Nonetheless, magnetic switching faces a tremendous challenge due to the inherently low switching speed of nanomagnetic devices. All magnetic devices to date are limited in switching speed by the fundamental precessional frequency of ferromagnetic materials. This frequency is generally in the range of 10 GHz and device switching speeds are in the range of 1 nanosecond. Therefore, a central goal of the nanomagnetics group has been to develop high-speed magnetic switching at the sub-10 picosecond level [14]. On the circuit/system level, the E^{3}S nanomagnetics theme has focused on developing in-memory and normally-off computing strategies using magnetic nonvolatile devices. The goal has been to evaluate the use of SRAMs enhanced with nonvolatile spin devices in general-purpose processing applications.

In period 9, the groups of **Jeffrey Bokor** and **Sayeef Salahuddin** (*Berkeley*) have focused on scaling ultrafast magnetic switching into the nanometer scale. Scaling is needed to reduce both the switching energy and current of ultrafast magnetic switching. This work is based on calculations that revealed energies and currents for the electrical switching of magnets could be in the femto-Joule and micro-Amps range, respectively, for a (20 nm)^3 cell size. These values would be suitable for integration with CMOS transistors. Related, the team is working on finding ultrafast switching magnetic compounds that do not lose their important perpendicular anisotropy upon scaling to the nanometer range.

The **Salahuddin** group has continued to understand the fundamental nature of spin transport and spin angular momentum transfer in spin-orbit coupled heterostructures. In the current period, the focus has been on exploring topological effects in spin-transfer torque devices. The group of **Shan Wang** (*Stanford*), who joined the Center this year (replacing **Philip Wong**) will also study topological effects in spin-orbit torque phenomena. Meanwhile, the goal of the group of **Sakhrat Khizroev** (*FIU*) has been to fabricate and characterize square spin-transfer torque based magnetic tunneling junction devices with sizes smaller than 2 nanometers. In collaboration with the **Bokor** group, the nanoparticle STT-MTJ concept has been used to write information not into two but into three layers and used the tunneling MR effect to read back information, paving the way for a new computing paradigm, which uses spin polarized currents to write and read back multilevel signal information.

Education & Diversity Strategic Plan

A central pillar of the Center's mission is education and broadening participation. The Center's vision is to set a legacy in the development of a next generation, engaged, skilled, and diverse workforce in energy efficient electronics that will last far beyond the sunset of this Center. The Center's primary goal is to develop Ph.D.- and M.S.-level scientists and engineers in energy efficient electronics science who: 1) are knowledgeable in the scientific approaches to energy efficient digital electronics systems; 2) understand that working in diverse teams enhances creativity; and 3) understand the process of innovation, entrepreneurship, and the transition of research results to commercially viable products. Supporting this primary goal is the Center's strategy of enhancing the number of students at all levels pursuing STEM education and, in particular, technical disciplines related to energy efficient electronics science to develop a pipeline of candidates for graduate studies. This pre-graduate level focus also serves to enhance a pipeline for technical disciplines beyond those in the Center, and for the future STEM workforce in general.

The Center has established programs to educate and develop its graduate student and postdoctoral researchers, as well as programs for high-school seniors, community college students, faculty, and upper division undergraduates.

Graduate Education

The Center provides formal and informal education. Since the start of the Center, E^{3}S Director, **Eli Yablonovitch** (*Berkeley*) biennially has taught a graduate level course on low energy electronics with a strong focus on E^{3}S topics and perspectives that the Center's students and postdocs can take either for credit or otherwise. In addition, the Center's faculty has incorporated into their courses general topics in low energy electronics, and in some cases, topics specific to the Center's research approaches and outcomes. Informal training occurs in the form of numerous presentations, mentoring, science communications, and other leadership opportunities in which the Center's students and postdocs participate. Given the number of opportunities available, the Center has also developed the E^{3}S Professional Development Program (E^{3}S PDP) to guide students and postdocs to acquire a diverse and balanced set of experiences. With this program, students are able to earn a Leadership Certificate if they have participated in many of the professional development opportunities. Frequently, the Center also offers training in areas that it deems important in the development of a scientist/engineer. Incoming students and postdocs are given ethics training when they begin in the Center. All mentors of REU students receive training in working with diverse groups, project management, and interactions between mentor and mentee. The Center has offered training in topics like Publishing Your Results, Entrepreneurship, Science Communications, Proposal Writing, and Best Practices to Promote Diversity.

Undergraduate Education

The Center uses Research Experiences for Undergraduates (REU) as the primary vehicle to engage undergraduates. There are three programs:

- ETERN provides paid internship during the academic year for undergraduates in E^{3}S member institutions to conduct research with E^{3}S faculty.
- E^{3}S REU provides paid summer internship primarily for students from 4-year institutions that are not associated with the Center.
- Transfer-to-Excellence (TTE) REU provides paid summer internship for California community college students to conduct research with E^{3}S and E^{3}S-affiliated faculty at *Berkeley*.

The Center has relied on the latter two programs to build a diverse pipeline for graduate school and into the Center. In particular, the Center chose a California community college focus because the California community college system is the largest in the US and these schools have traditionally been the preferred first stop in undergraduate education for women, underrepresented minorities, and first generation college students. After seven years of operation, the Transfer-to-Excellence (TTE) program has enabled not only higher transfer rates of California community college students to STEM baccalaureate programs, but has enabled its participants to transfer to top four-year institutions. TTE alumni, who were interns in the laboratories of E^{3}S or E^{3}S affiliated faculty, have been transferring to four-year institutions since Fall 2012 at a rate of 94%, with most transferring to Tier 1 academic institutions.

The recruiting of underrepresented groups including women and racial minorities is emphasized across the spectrum of the education programs. Furthermore, the Center is concerned with improving access and supporting first-generation college students, veterans, persons with disabilities, and those from lower income backgrounds to be able to successfully transition to an academic environment or the STEM workforce. While the rate of students entering graduate school among the E^{3}S REU program alumni is high, the rate that students are transferring into the Center is still somewhat low. Even though a substantial percentage of alumni continue their graduate degree at an E^{3}S member institution, they do not pursue a thesis in an E^{3}S area of research. The Center recognized this difficulty and addressed the challenge through structural changes. In period 6, the E^{3}S Executive Committee decided to separate the management of the function of education and diversity. Now, the Center has an Associate Director of Education, who is responsible for education, and a Director of Diversity who is responsible for diversity and outreach.

The Diversity Director has been continuing efforts to increase representation such as creating a heightened awareness about the Center, using targeted recruitment (from large databases) to find potential students, creating or enhancing partnership opportunities with minority-serving institutions, and working towards promoting and sustaining a climate of inclusive excellence.

The Center also seeks to impact community college education by offering professional development opportunities to community college faculty. Community college faculty members have conducted research at the laboratories of E^{3}S faculty. In addition, they also have the option to develop new teaching materials advised by E^{3}S graduate students or postdocs. The Center has augmented this professional development program by offering a series of pedagogy workshops in partnership with the Berkeley Center for Teaching and Learning. Regardless of whether the professional development experience is in research or curriculum development, the community college faculty participants are expected to implement new teaching materials in their classroom upon their return to their home institution.

Online Education

The Center looks to build its education legacy with online education and training materials that relate to the Center's research focus. This strategy was adopted in the Center's 4th year. This strategy is expected to have impact at all levels: developmental experiences for the Center' graduate students, postdocs, and staff, as well as educational resources and knowledge transfer venue for a wide range of audiences. A 1.5-hour mini-course in Energy Efficient Electronics for entry-level graduate students has been in development. Also in development is an e-book that is geared towards a high-school audience. The Center has completed a first draft of Theme 2, and work continues towards completing a draft for the remaining three themes by the end of period 9.

Knowledge Transfer

Knowledge transfer is thus at the heart of the Center for E^{3}S mission as an NSF Science and Technology Center. E^{3}S is dedicated to search for groundbreaking scientific discoveries and fertilize new technologies, and associated knowledge transfer activities and outcomes are considered a key metric of its success. Since its inception, the Center for E^{3}S has recognized the importance of establishing partnerships in accelerating research, education and outreach endeavors. At the same time, the Center has put significant efforts into sharing new knowledge with industry, academia, research labs and the general public.

The Center's knowledge transfer strategy involves all of the E^{3}S industry and education partnerships to serve as venues for introducing new and more efficient electronics technologies. As the Center's research results lead to changes in directions and approaches, it is critical that the Center's sharing of knowledge will lead to a community of like-minded research peers who together can accelerate the achievement of the goal of milli-Volt switching and few-photon communications.

Recognizing that education is itself an important knowledge transfer element, the Center prepares its students and postdoctoral members to be the next-generation knowledge-transfer practitioners, who will have opportunities to communicate science to audiences at all levels. The Center leverages the expertise and resources of its partners to deliver on its promise to prepare a new diverse generation of STEM workers. We are contributing to engineering and science education through publications and presentations, covering what we learn in the design, execution and evaluation of our programs.

Summary of the Center for E^{3}S Performance in Period 9

In this section, a summary of the progress of the Center for E^{3}S in period 9 is presented. Details and in-depth analyses of the results are given in the following sections of this report.

As has been done in previous periods, the state of the Center is presented with respect to the E^{3}S Strategic Plan 2015-2020, and the metrics established therein. Performance targets set in the E^{3}S Strategic Plan 2015-2020 not only create a pathway for repeated internal analysis of results and research directions, but also facilitate reporting of results on a period-by-period basis.

Table 1.1. *Center for E^{3}S Performance Targets and Results*

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Research	Multi-PI projects	P2: 30% P5: 75% P6: 50% P7: 60% P8-P10: 70%	44%	67% (14)	55% (12)	64% (14)	76% (13)	65% (11)	79% (15)	89% (16)
	Multi-Institutional projects	P2: 10% P5: 30% P6: 15% P7: 20% P8-P10: 25%	4%	10% (2)	9% (2)	23% (5)	29% (5)	29% (5)	32% (6)	72% (13)
	Publications with authors from multiple institutions	P3: 12 P4: 3 P5-10: 5	0	0	1	1	3	5	2	6
	New joint research funding awards	P6: 1 P7: 0 P8-P10: 1	(new for P6-10)				0	3	1	1
Education	Center graduates completed E^{3}S training	P2: Baseline P3-5: 50% P6: 15% P7: 30% P8: 40% P9: 50% P10: 15%	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)	5 (36%)	3 (23%)
	E3S graduate students taking online course taught by Center director	P6, 8, 10: 0 P7, 9: 10	(new for P6-10)				0	8	0	6

	Undergraduates who pursue advanced degree in science and engineering	P3: 5% P4: 30% P5: 35% P6: 40% P7: 45% P8-P10: 50%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)	36 (69%)	41 (73%)	47 (70%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P2: Baseline P3: 5% P4-5: 80% P6-10: 85%	n/a	3 100%	6 100%	7 100%	6 100%	4 80%	4 60%	6 100%
	Pre-college students who pursue a bachelor's degree in science and engineering	P3: Baseline P4-5: 70% P6-10: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)	180 (47%)	TBD
	Students and postdocs serving in leadership roles in the Center	P2: Baseline P3: 15% P4: 20% P5: 25% P6-8: 30% P9: 20% P10:15%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)	14 (16%)	17 (21%)
Diversity	Women in the Center's research programs	P2: Baseline P3: 5% P4: 30% P5: 20% P6-10: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)	12 (14%)	20 (23%)
	Underrepresented minorities in the Center's research programs	P2: baseline P3: 15% P4: 5% P5-6: 10% P7-8: 12% P9-10: 15%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)	11 (13%)	15 (17%)
	Participants from underrepresented* groups in the Center's Diversity programs	P3: Baseline P4: 80% P5: 85% P6: 85% P7: 85% P8-P10: 85%	n/a	n/a	Women 37 (44%)	Women 26 (41%)	Women 29 (40%)	Women 25 (40%)	Women 38 (44%)	Women 40 (42%)
					URMs 58 (68%)	URMs 36 (56%)	URMs 49 (67%)	URMs 38 (60%)	URMs 48 (55%)	URMs 50 (58%)
				Total 93 (82%)	Total 73 (86%)	Total 49 (77%)	Total 66 (90%)	Total 63 (87%)	Total 69 (80%)	Total 68 (77%)

	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center	P6: 40% P7: 45% P8-P10: 50%	(new for P6-10)				17 (55%)	23 (54%)	27 (50%)	30 (55%)
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate	P6: 85% P7: 85% P8-P10: 85%	(new for P6-10)				16 (70%)	22 (81%)	24 (80%)	30 (88%)
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering	P6: 80% P7: 80% P8-P10: 80%	(new for P6-10)				73 (55%)	102 (63%)	14 (33%)	TBD
Knowledge Transfer	Center publications	P2-5: 18 P6-7: 25 P8-P10: 30	21	21	27	46	39	37	31	39 (7 subm)
	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26	21
	Center sponsored symposia & workshops	P2: Baseline P3: 0 P4: 1 P5: 0 P6: 2 P7-9: 1 P10: 2	1	0	1	0	1	1	2	2
	External citations of publications *(cum)*	P3: 10 P4-5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase	6076 40% increase
	Industry contacts:									
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2

	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8	7
	Patent disclosures									
	• Disclosure/Provisional	P3: 3 P4: 3 P5: 5 P6: 2 P7: 2 P8: 3 P9-P10: 4	1	0	1	0	2	1	4	0
	• Patent/Patent Application	P4: 0 P5: 3 P6: 1 P7-P9: 2 P10: 3	1	2	1	3	8	4	1	2
	Technologies attributable to Center's research		(new for P6-10)				0	0	0	1
	• Low energy devices	P6-P9: 0 P10: 1								
	• Enabling other applications	P6-7: 0 P8-P9: 1 P10: 2								
	Center's alumni into relevant industries	P5: 50% P6-7: 30% P8-P9: 40% P10: 50%	Student 0%	Student 64% (7)	Student 16% (2)	Student 16% (6)	Student 50% (12)	Student 22% (2)	Student 33% (4)	Student 22% (2)
			Postdoc 100% (1)	Postdoc 33% (2)	Postdoc 20% (2)	Postdoc 40% (4)	Postdoc 13% (1)	Postdoc 18% (2)	Postdoc 60% (3)	Postdoc 0
	Center's alumni pursuing research in academia & research labs in disciplines related to the Center	P6-10: 30%	(new for P6-10)				Student 38% (9)	Student 78% (7)	Student 58% (7)	Student 56% (5)
							Postdoc 88% (7)	Postdoc 82% (9)	Postdoc 40% (2)	Postdoc 83% (5)
Center Management	Annual Surveys:	Measured and reported on Likert Scale								
	• Students /Postdocs	P2-5: 3 or higher	Average 3.9±0.2	Average 4.0±0.3	Average 4.2±0.2	Average 4.5±0.2	Average 4.3±0.2	Average 4.3±0.3	Average 4.4±0.1	Average 4.3±0.2
	• Co-PIs	P6-10: 4 or higher	No survey	Leadership 4.46	Leadership 4.7±0.5	Leadership 4.9±0.1	Leadership 4.6±0.1	Leadership 4.8±0.2	Leadership 4.8±0.1	Leadership 4.8±0.1

	• External Advisory Board		Strategic Plan: 4.2 Center Status 4.0	Strategic Plan: 4.1 Center Status 4.0	Strategic Plan: 4.6 Center Status 4.6	Strategic Plan: 4.4 Center Status 4.7	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	N/A
	Authorship disputes	P2-5: 20% decrease P6-10: 0	0	0	0	0	0	0	0	0
	Plagiarism	P2-10: 0	0	0	0	0	0	0	0	0
	Changes in Center processes made in response to evaluation results	3 months for closure of regular action; 1 week for closure of time-sensitive action	(new for P6-10)				0	0	0	0

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

Research Accomplishments in Period 9

The Center for E^{3}S brings together faculty researchers from five academic institutions: University of California, Berkeley (*Berkeley*), Massachusetts Institute of Technology (*MIT*), Stanford University (*Stanford*), The University of Texas at El-Paso (*UTEP*), and Florida International University (*FIU*).

In period 9, the Center's faculty researchers have been:

- *Berkeley*: Jeffrey Bokor, Constance Chang-Hasnain, Felix Fischer, Ali Javey, Tsu-Jae King Liu, Steven Louie, Sayeef Salahuddin, Vladimir Stojanović, Junqiao Wu, Ming C. Wu, Eli Yablonovitch
- *MIT*: Vladimir Bulović, Jesus del Alamo, Eugene Fitzgerald, (will phase out of E^{3}S by end of period 9), Jeehwan Kim (will join E^{3}S at the end of period 9), Jing Kong, Jeffrey Lang, and Timothy Swager
- *Stanford*: H.-S. Philip Wong (left E^{3}S on July 1, 2018), Shan Wang (joined E^{3}S on September 1, 2018)
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

Theme I: Nanoelectronics – Key Accomplishments

- *III-V Nanowire TFETs:* For the study of the underlying physics of tunneling in semiconductors, vertical nanowire (VNW) III-V TFET structures developed by the **del Alamo** group have proven to be excellent model systems [2, 15, 16]. In particular, these systems give insights into the issue of defect assisted tunneling in the OFF-state. In this period, the **del Alamo** group succeeded in fabricating working InGaAs VNW MOSFETs with record nanowire diameters as low as 7 nm, a regime in which prominent single-channel electron transport is to be expected [17]. This latest result was enabled by the recently developed solvent-based digital etch technique and the use of alloyed Ni contacts, which remained conducting down to diameters of 7 nm [18]. While device currents are currently rather small, the group has identified several avenues for improvement, including mitigation of parasitic effects and optimization of top contact design and sidewall interface defect control. In a collaboration with the group of Steven George (*University of Colorado*, *Boulder*), the **del Alamo** group also developed a thermal atomic layer etching (TALE) method for InGaAs and InAlAs and demonstrated InGaAs FinFETs through *in-situ* TALE and atomic layer deposition (ALD) of the gate oxide [19]. This constitutes the first transistor demonstration fabricated by *in-situ* TALE+ALD of any kind in any material system. The big advantage of this method is a greatly increased interface quality control. The resulting devices thus have far better ON- and OFF-state characteristics than similar devices fabricated by conventional techniques. This opens new avenues for the fabrication of TFETs with vastly improved interface characteristics, which will be critical to study single-channel transport, as predicted by the **Yablonovitch** group's modeling work on single 1D subband devices.

- *Spectroscopic Line-Shape of Tunneling Energy Levels:* Since the preferred energy filtering mechanism for tunnel transistors relies upon the quantum level energy alignment, knowledge of the shape of the spectral tails of the energy levels is of great importance. The steepness of the spectral tails translates directly into steepness and sensitivity of the tunnel transistor response. The most common model in physics for the expected spectral shape of an energy level is the famous Lorentzian line-shape. However, since the spectral wings of a Lorentzian fall very slowly from line center, it becomes difficult to turn the transistor off, and to achieve the required 10^6:1 ON/OFF ratio. The **Yablonovitch** group showed that, fortunately, the Lorentzian line-shape is only an approximation, and investigated and developed auto-correlation functions that behaves correctly; i.e. it is exponential at long times, but parabolic at short times.

- *Layered Chalcogenide TFETs:* Recognizing that sharp subthreshold swings in 2D-TMDC TFETs can only be achieved by highest quality chalcogenide materials, the **Kong** group started to use MOCVD for the growth of large area 2D monolayers. In this period, growth efforts have intensified and successful growth of monolayer MoS_2 with a measured field effect mobility of ~45cm^2/Vsec has been demonstrated. The **Kong** group has also succeeded in the synthesis of the 2D monolayer semimetals TiS_2 and VS_2 by ambient pressure CVD. Using *in-situ*-generated titanium chloride gaseous precursor, the group was able to grow large-area, highly crystalline 2D TiS_2 nanosheets with controlled size, shape, and thickness. Furthermore, the group developed a two-step CVD strategy that enables the synthesis of solely TMDC-based semimetal-semiconductor lateral heterostructures (e.g., MoS_2-VS_2 stitches). Remarkably, in such heterostructures, MoS_2 was found to nucleate from the vertexes of multilayered VS_2 flake and evolve into a polycrystalline monolayer film surrounding the VS_2 flake. Compared to the lithography and lift-off processes required for fabricating metal-semiconductor contacts in silicon technology, direct synthesis of such lateral heterostructures enables straightforward fabrication of all-TMD-based electronics with atomic thickness. The transistors fabricated with solely TMD-made metal-semiconductor contacts exhibited contact resistance as low as 500 $\Omega \cdot \mu$m, which is two orders of magnitude lower than in previous reports for polycrystalline monolayer MoS_2 [20].

  The **Javey** group continued to focus on 2D material engineering to achieve better device performance through material quality improvements. In this period, the group succeeded in directly measuring the edge recombination velocity of several few-layer TMDC materials by scanning probe lithography (SPL) patterning. The various parameters such as voltage bias, amplitude setpoint, and humidity that effect SPL of 2D materials were analyzed and tuned to reach sub-100 nm resolution. In addition, the **Javey** group gained new insights into radiative processes in 2D-TMDCs. The group demonstrated that the photoluminescence quantum yield of as-exfoliated MoS_2 and WS_2 monolayers reaches near unity when the monolayers are made almost intrinsic by electrostatic doping, revealing that, even in the presence of defects in sulfur-based TMDCs, neutral exciton recombination can be entirely radiative. They also showed that the most effective chemical passivation of 2D-TMDC monolayers, using bis(trifluoromethane)sulfonamide, is predominantly electron counter-doping.

- *Graphene Nanoribbon Quantum Tunneling Structures:* In period 9, the group of organic chemist **Felix Fischer** has continued to lead the experimental aspects of this project with broad theory support by **Steven Louie** and **Eli Yablonovitch.** In addition, the group of **Jeffrey Bokor** provides guidance in integrating GNRs into FET device architectures. In the last period, the E^{3}S GNR nanoelectronics group identified the development of GNRs with a metallic band structure (VB/CB overlap ~ 0.1 eV) as high priority. In response, the **Louie** group identified several synthesizable metallic GNR structures using density functional theory (DFT) calculations. Using these theoretical results, the **Fischer** group is currently synthesizing a series of GNR molecular precursors for polymerization into GNRs.

A major achievement in the current period has the successful demonstration that symmetry protected topological states can be rationally engineered into bottom-up synthesized GNRs [21]. This discovery presents an entirely new route to band engineering in monolayer materials based on precise control of their electronic topology. The **Louie**'s group theoretical work had predicted the existence of 1D symmetry-protected topological phases in GNRs [22]. The **Fischer** group then successfully demonstrated for the first time the rational design and experimental realization of a topologically engineered GNR superlattice that hosts a 1D array of topological states, thus generating otherwise inaccessible electronic structures. The experimental results and first-principles calculations revealed that the frontier band structure of these GNR superlattices is defined purely by the coupling between adjacent topological interface states. This represents an entirely new strategy to access metallic states and unusually sharp energy levels (ΔE ~ 5 meV), which the **Yablonovitch** group has recently identified as critical for the successful realization of TFET architectures.

Theme II: Nanomechanics – Key Accomplishments

- *Ultra-Low-Voltage Relay Design and Operation:* In period 9, the **Liu** and **Wu** groups focused on further improvements of the NEM relay design and low-voltage operation with the goal of reducing both the relay switching hysteresis voltage (VH) and sub-threshold swing. The **Liu** group developed an improved body-biased relay design for reducing contact stiction. In contrast to the previous four contact dimples "4C" design, a new "2C" design has been developed with only two contact dimples (one for each electrical switch). The result was a smaller total contact area and hence lower adhesion force (FAD) as well as lower ON-state resistance (RON) [23]. Comparison of the old and new designs revealed that VH is lower for the 2C devices compared to 4C. In addition, VH was also much lower for relays coated with an anti-stiction layer of PFOTES (perfluorooctyltriethoxysilane) molecules due to reduced surface adhesion energy between contacting electrode surfaces. The subthreshold swing (SS) is approximately twice as large for the 4C design compared to the 2C design, since twice as much force is needed to compress the PFOTES molecules in a 4C relay.

  The **Wu** group joined forces with the **Liu** group in the study of new anti-stiction surface coating molecules to further reduce surface adhesion of NEM switches without degrading their conduction. They systematically investigated self-assembled molecular coatings with various chain lengths and found out that to reduce adhesion, more CF2 molecules must be added to the chain, however, this would degrade conduction as the self-assembled molecular coating is insulating. The best results were obtained from molecular coatings with branched tails, such as perfluoro(2,3-dimethylbutan-2-ol). With this approach, relays with VH as low as 20 mV with abrupt switching were achieved. A 62% reduction in hysteresis and 52% reduction in average switching slope was achieved without affecting the instantaneous switching slope.

- *Sub-100 mV Relay-Based Digital Integrated Circuits:* The **Liu** group has continued their collaborative work with the **Stojanović** group toward the goal of demonstrating reliable operation of relay-based digital integrated circuits (ICs). Using the significant NEM relay improvements of the 2C design and the application of optimized anti-stiction coatings, the team achieved a major milestone in this funding period: reliable room-temperature operation of a variety of relay integrated circuits at a voltage of 50 mV. Various two-input logic functions have been implemented with only two relays using pass-gate circuit topology, including NOT, AND, OR, and XOR logic gates, all functioning at 50-mV operating voltage [24]. The team also showed that pass-gate circuit topology minimizes the number of mechanical delays and the number of relays per digital function by demonstrating a 2:1 multiplexer using only two relays [25]. For comparison, a CMOS implementation requires at least four transistors. The source electrode of each relay acts as an input signal line; the gates are connected together to form a select line; and the drain electrodes form interconnects at the output node. The demonstration of reliable operation of relay-based digital ICs at voltages of 50 mV is a major legacy achievement of the Center for E^3S.

- *Squitch: Molecular Squeeze-Switch:* The **Bulovic**, **Lang** and **Swager** groups, the **Squitch** team, has focused on improving fabrication yield and squitch device performance. The group found that two steps of squitch fabrication are particularly important since both of them involve the self-assembly steps: the formation of the molecular monolayer that occupies the squitch tunneling gap, and the placement of gold nanorods above the squitch electrodes using dielectrophoresis. At present, the molecular monolayer comprises thiolated polyethylene glycol. In addition, the yields of the critical squitch fabrication steps were characterized, and with the exception of the dielectrophoretic trapping of suspended gold nanorods, all steps exhibited nearly 100% yield. Trapping, on the other hand, was measured to have a yield less than 20% depending on the voltage amplitude and frequency of the excitation used to drive the dielectrophoresis. The reasons for this lower yield include the tendency of gold nanorods to agglomerate in suspension, and the fact that the gold nanorods are only weakly bonded to the molecular monolayer. Therefore, as the dielectropheresis solution dries, the receding edge of the solution can carry a nanorod off the electrodes.

  The team also characterized the conduction process and switching delay of squitch devices. Two-terminal squitches have been measured to actuate at approximately 2 V, and exhibit a subthreshold slope of approximately 40 mV/decade over 5 decades of current. The switching delays of two-terminal devices are typically in the 20-40 ns range as an upper bound. Improved experimentation will be performed in the future to determine the switching delay more accurately. It was found that the molecular monolayers play a critical role in squitch devices. To gain detailed insights into the mechanical behavior of the commonly used polyethylene glycol molecular monolayer during squitch cycling, a novel metrological experiment was conducted. This examination has revealed that the monolayer permanently deforms as the squitch gap is closed and opened. Interestingly, this behavior was not observed with earlier molecular layers formed from fluorinated alkane thiols.

- *Stritch: 2D Chalcogenide Stretch-Switch:* The stritch device is a stretch-switch operating by stretching a 2D-TMDC layer using a MEMS actuator, and thereby changing its bandgap and conductivity. The **Stritch** team comprises the **Zubia** group, in close collaboration with the **Liu**, **Javey** and **Wu** groups. In this period, a new comb-drive MEMS actuator was fabricated to overcome design problems identified in the last period: residual stress damage and finger deformation at high voltages. 2D-TMDC samples were transferred onto the new actuator to test their electrical and optical properties under strain. The group demonstrated a 3000-fold increase in conductivity in MoS2 flakes stretched to a record 3% strain. Photoluminescence and Raman measurements corroborated the electrical data. To achieve the demonstrated 3000-fold conductivity increase in MoS2 by straining, vertical actuation was used instead of horizontal actuation as originally intended, which limited the strain to a maximum of 3%, however. To allow for optical measurements to be made simultaneously with electrical measurement, a simplified MEMS actuator, which should improve manufacturability as well as testability, was designed with the aid of 3-D simulations. This new actuator design will be fabricated and tested in period 10.

Theme III: Nanophotonics – Key Accomplishments

- *Antenna-Enhanced III-V nanoLEDs:* The **Wu** and **Yablonovitch** groups at *Berkeley* have continued their close collaboration with the **Fitzgerald** group at *MIT* (and recently with the **Kim** group at *MIT*) with the goal to further optimize the efficiency and direct modulation rate of the III-V antenna-LED developed at E^{3}S [26, 27]. In this period, the group succeeded in performing time-resolved photoluminescence studies of the spontaneous emission lifetime of the III-V antenna-LED. These first-of-a-kind measurements for antenna-enhanced nanoLEDs revealed ultrafast spontaneous emission lifetimes in the 50 ps range at 77 K. A ~30-fold reduction in the lifetime was observed for the device with antenna compared to a bare emitter without antenna. This is the "overall" enhancement averaged over the entire spontaneous emission spectrum, whereas previously it was only possible to report the maximum enhancement. The nanophotonics team also started exploring ways to overcome Ohmic loss due to spreading resistance and the anomalous skin effect. A metal-dielectric antenna design has shown promise by using dielectric tips to efficiently concentrate light near an optical emitter. For feature sizes less than 10 nm, the efficiency of the metal-dielectric antenna is constant and achieves ultra-high broadband spontaneous emission enhancement relative to the all-metal antenna. Use of a similar metal-dielectric antenna could enable efficient, ultra-fast next-generation LEDs.

In this period, the **Wu** group also teamed up with **Michael Bartl** (*Berkeley*) and started a new project to incorporate colloidal quantum dots into the antenna-LED emitter. Quantum dots have several benefits such as wavelength tunability, high efficiency, and flexibility in processing including the use of arbitrary substrates. In initial studies, the group successfully integrated colloidal CdSeS/ZnS quantum dots into a slot antenna active region. This was achieved by selective-area deposition of the quantum dots into the slot region. Initial photoluminescence studies confirmed the selective-area deposition. Currently, the team works on eliminating undesirable light emission from outside of the slot region. This "off-slot" light emission will need to be reduced in order to measure the spontaneous emission lifetime and determining the antenna enhancement of the spontaneous emission.

- *Chalcogenide Antenna-LEDs:* Following the successful demonstration of bright electroluminescence at ambient conditions by pulsed electrical injection of WSe_2 monolayers [28], the **Wu** group, in collaboration with the **Yablonovitch** and **Javey** groups, sought to understand the underlying mechanism for this bright emission. In particular, they have investigated the physical mechanisms responsible for improved light emission with pulsed injection at ambient conditions. Results obtained so far point to ambient humidity as well as intrinsic hole trapping as the dominant mechanisms causing current decay at ambient conditions. In addition, significant effort was made toward optimizing the process conditions to obtain the highest electroluminescence quantum efficiencies to date (~1%). In fact, this value is comparable to the photoluminescence quantum efficiency, indicating efficiency is limited primarily by material quality. The quantum efficiency values are on par with the best results in the literature [29, 30]. The next steps of this project will aim at coupling these devices to antennas and enhance emission speed and efficiency.

- *Coupling of nanoLEDs to Optical Waveguides:* In this funding period, the **Wu** group in collaboration with the **Yablonovitch** and **Chang-Hasnain** groups, made significant progress in the coupling efficiency and overall performance by applying electromagnetic inverse design techniques. The starting structure was an antenna nanoLED coupled to an InP waveguide in the tapered coupler design. The tapered coupler design was then allowed to structural evolve through a combination of hand optimization and inverse design optimization *via* the adjoint method. The important device characteristics in the optimization process were the coupler average (spectral, spatial, and polarization averages) enhancement, F_{ave}, which is indicative of the device speed (e.g., $F_{avg} > 100$ corresponds to ~100 GHz direct modulation rate), and the total waveguide-coupled external quantum efficiency, η_{WCEQE} (which includes metal losses). The optimized coupler design is capable of >95% coupling efficiency, corresponding to 60.8% total waveguide-coupled external quantum efficiency. Importantly, the overall enhancement, including polarization and spatial averaging, of the device is 143.5, which would enable >100 GHz direct modulation. Moreover, the optimized structural design is fully compatible with top-down fabrication methods. Efforts in the upcoming research period will be directed to apply the theoretical analysis and toward an experimental demonstrate of an optical link.

With this optimized waveguide-coupled antenna-enhanced nanoLED in hand, the **Wu**, **Stojanović**, and **Yablonovitch** groups teamed up to simulate a full digital-to-digital optical link with inclusion of the receiver. The receiver model considers not only resistor thermal noise and transistor FET noise, but also the input swing sensitivity required to have an output rail-to-rail signal. All of these metrics combine to yield a topology and data-rate specific energy-per-bit (E/b) both for the receiver side and transmitter side. For each data-rate, an optimization was performed to find the minimum E/b sweeping over the number of linear amplifiers, the number of interleaves, and the FET sizing. The group found that E/b values below 1 fJ/bit can be achieved for data rates of up to 100 Gbps assuming high fT of 260 GHz within the receiver. Such high fT is achievable with 22 nm FDSOI technology. Ultimately, the nanoLED power imposes a restriction on the maximum attainable data-rate for the link. Due to a small active region it is constrained to approximately 2-3 μW of output power. The team is currently pursuing improved nanoLED design to further increase the output power.

Theme IV: Nanomagnetics – Key Accomplishments

- *Picosecond Magnetic Switching:* The **Bokor**, **Salahuddin**, and **Wong** groups have joined forces to integrate magnetic device structures on advanced CMOS chips in order to realize ultrafast magnetic switching and readout triggered by electrical pulses generated directly by CMOS circuits. In period 9, research efforts have been directed to address a key challenge: reduction of both the switching energy and current by scaling the magnetic switching structure into the nanoscale. Calculations revealed that energies and currents for the electrical switching of magnets could be as low as ~3.5 fJ and ~10’s of μA, respectively, for a (20 nm)^3 cell size, which would be suitable for integration with CMOS transistors. While many magnetic compounds lose their important perpendicular anisotropy, the **Bokor** and **Salahuddin** groups discovered that GdCo and GdTbCo alloys maintained good perpendicular anisotropy upon scaling into sub-micrometer range. In fact, for the GdCo alloys, ultrafast all-optical switching behavior was observed in nanoscale dots fabricated in arrays down to 200 nm diameter.

  In addition, the team is working on the design and fabrication of suitable microwave circuits, which will deliver the required short electrical pulses to switch the device, and detect the magnetic state of individual dots. Good progress has already been made in this effort, and a Hall-cross device geometry capable of measuring the magnetization in GdCo nanodots down to 50 nm diameter has been successfully fabricated and tested. Simulation studies of pulse propagation on microwave striplines have guided the design for the integration of this Hall bar structure into a microwave stripline that will generate the picosecond electrical pulse and deliver it to the Hall bar. Fabrication of these structures is currently in progress.

- *Spin-Orbit Torque Switching:* In period 9, the **Salahuddin** group started a new direction in the quest on devising ways to reduce current needed to switch magnets by investigating spin transfer torque in topological insulator materials. Harmonic measurements of the longitudinal and transverse voltages in Bi-Sb/Co bilayers were investigated and a large second harmonic voltage signal due to the ordinary Nernst effect was observed. When a magnetic field is rotated in the film plane, the ordinary Nernst effect shows the same angular dependence in the transverse voltage as the damping-like spin-orbit torque and in the longitudinal voltage as the unidirectional spin-Hall magneto-resistance, respectively. Therefore, the group identified the ordinary Nernst effect as a source of observed effects in spin-orbit torque experiments, leading to an overestimation of the spin-Hall angle in topological insulators or semimetals.

In this period, **Shan Wang** joined the Center for E^{3}S, bringing new expertise in the area of spin–orbit torque switching into the Center. His group will work closely with the **Salahuddin** group on using topological effects for energy-efficient computing and spin-orbit torque switching. In addition, the **Wang** group is currently investigating a new two-terminal spin-orbit torque MRAM cell based on a CoFeB/MgO magnetic tunnel junction pillar on an ultrathin Ta underlayer. In this device, in-plane and out-of-plane currents are simultaneously generated when a voltage is applied.

- *Magnetic Tunneling Junction Devices:* The **Khizroev** group has continued to study the dependence of the spin torque transfer (STT) switching current density on the device size. Calculations predict that ultra-high magnetoresistance values should be obtained for sizes below 5 nm. In this period, the **Khizroev** group, in collaboration with the **Bokor** group, have built first batches of nanoparticle-based STT magnetic tunnel junction (MTJ) devices with critical sizes as small as 2 nm. Superior properties such as extremely high equivalent "ON/OFF" ratios with tunneling MR values exceeding 1000%, and record low switching current densities (< 1 MA/cm^2) were observed for these devices. The group then used this nanoparticle STT-MTJ concept combined with electron-beam lithography nanofabrication to write information not into two but into three layers and used the tunneling MR effect to read back information. The written/read back information had a ternary (not binary) signal format [31]. These results will pave the way for a new computing paradigm, which uses spin polarized currents to write and read back multilevel signal information.

System Integration – Key Accomplishments

- From the very start of the Center for E^{3}S, System Integration was regarded as an important and integral part of its research endeavors. System Integration at E^{3}S overarches the four research themes (nanoelectronics, nanomechanics, nanophotonics and nanomagnatics) as an integral "control organ". It checks that the component research outcomes and new scientific device concepts of the Center will actually lead to new energy-efficient system architectures, enabling future ultra-low power information technologies. In addition, to this "control organ" function, in the last period, under the leadership of **Vladimir Stojanović** (*Berkeley*), System Integration has started a new direction by setting up a deep-learning training environment based on a tensor flow approach. This approach should enable evaluation of various hardware-related architectural tactics (network pruning, reduced resolution, *etc*.) and system-level evaluation of E^{3}S-relevant computing architectures (including NEM-relay ICs and spin-Hall memory devices integrated with a CMOS latch).

- In this period, the **Stojanović** group has developed a flexible reference architecture for artificial intelligence (AI) workloads tailored to the present and future AI algorithms. This reference architecture was designed to lower the energy per task by minimizing the data movement, enabling localized computation and sets the stage for further innovation through E^{3}S device and process research. To establish a clear benchmark to emerging E^{3}S technologies, a full accelerator instance was designed and implemented in an advanced CMOS node (16 nm). It achieves 50 Tops/W (20 Top/s at 0.4 W), which represents a 50 to 100-fold improvement over the latest inference engines (TPU3, PX Xavier, Stanford EIE). The architecture of the accelerator has routing matrices, which allow for reconfiguration of the neural network layer to form dense localized block-level operation and coefficient weight/result memory accesses. The routing blocks further perform randomization of the dense blocks to recreate the typical fully connected layer sparsity. The generator allows to extract the power and area metrics for a variety of design instances, exploring the architecture trade-offs and understanding the role of each sub-block component and the opportunity for improvements through the use of advanced device technologies pursued in E^{3}S (for example the NEM relay-based non-volatile memories and reconfigurable interconnects).

Education and Diversity Accomplishments in Period 9

The Center offers a variety of practical training opportunities for graduate students and postdocs, including both oral and poster presentations, presenting at seminars and during Center events, mentoring of undergraduates, group analysis of competing research, participating in the REU intern selection process, serving as poster judges, and conducting scientific demonstrations at outreach events. Given the number of opportunities available, the Center has developed the E^{3}S Professional Development Program (E^{3}S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences. Upon completing four development areas, a student/postdoc will receive a Leadership Certificate. Thus far, 24 students have earned a certificate of completion.

Intended to be pathway programs, the E^{3}S and TTE REU Programs, are designed to continue engagement after the internships end. Post program engagement comes in three ways: 1) a travel award to present the research outcomes of the internship at a conference; 2) advice and support through the application process for either transfer admissions to a four-year institution and/or graduate school; and 3) annual surveys to track the progress of the program alumni. In period 9, eight REU alumni presented their research at a conference. Three TTE alumni gave poster presentations at the 2018 SACNAS annual conference, three E^{3}S REU students presented their work at the 2018 SWE annual conference, one E^{3}S REU student presented their work at AIChE, and one E^{3}S alumni presented their work at Delta State. In addition to these conference presentations, one E^{3}S REU student presented their poster at this year's E^{3}S annual retreat and one student has been published in Nature Communications.

The Center has a strong record of REU program alumni going on to transfer and further their careers in graduate education. To date, 75% of undergraduate REU alumni have enrolled in a graduate program in science or engineering and 100% of community college students who did research with E^{3}S or E^{3}S affiliated faculty last year have transferred to a four-year university with 67% transferring to Berkeley.

Knowledge Transfer Accomplishments in Period 9

Knowledge transfer is at the heart of the Center for E^{3}S mission and vision to foster groundbreaking new science discoveries and fertilize new technologies. As in previous years, dissemination of results and outcomes from research, education and diversity activities has remained the key knowledge transfer avenue of the Center. In period 9, E^{3}S has continued its strong record of knowledge transfer through a range of activities, including disseminating results and outcomes from research and education, organizing national meetings and workshops, using social media and other new platforms to reach a broad community of scientists and engineers, and establishing the foundation for a lasting Center research and education legacy.

The Center informed the scientific community and general public about recent findings through publications in scientific peer-reviewed journals, presentations at peer-reviewed conferences, scientific meetings, universities and industry, and knowledge exchange with a wide range of communities via public and private meetings. Detailed numbers are given in Table 1.2. Knowledge transfer into the Center has continued through regular seminars and visits with the Center's Industrial Research Board and other companies the Center considers key players in low-energy electronics. Interactions occurred at multiple levels, including seminars by invited external speakers, Center students and postdocs visiting companies to learn about other low-energy electronics programs, and co-sponsorship of and participation in the BETR (Berkeley Emerging Technologies Research) Center's biannual meetings.

Furthermore, this year, the Center for E^{3}S was selected to organize the 2018 STC Directors Meeting (August 21-22, 2018 on the UC Berkeley campus). The topic of this meeting was "Engaging Diverse Audiences: Broadening Participation through Science Communication" in recognition of the increasing importance of communicating science and engineering to a broad community. The meeting featured presentations and panel discussions by an exciting line-up of speakers from various areas of science communication (TV, radio, online and print media, science museums, etc.; see Appendix G for detailed program), video presentations, a tour of the San Francisco Exploratorium, and several general networking opportunities. The meeting attracted 125 registered attendees and brought together leadership teams from all 12 current STCs in the country with five NSF program directors and officers. In addition, with supplement funding from the NSF we were able to bring thirty students from current STCs to the Berkeley campus to participate in the meeting as well as in several professional development activities.

The Center organized the inaugural Gender Bias Workshop in partnership with the Women in Technology Initiative (WITI) in spring 2018. This workshop focused on gender bias in technology and provided a virtual reality experience on what it is like to be a young female coder in a male-dominated startup environment. All 36 available spaces were filled quickly. Follow-up workshops are planned.

Lastly, in this period, E^{3}S has further accelerated its efforts and creating a lasting and impactful Center legacy in both research and education. With input from the E^{3}S External Advisory Board and the E^{3}S Industrial Research Board, the leadership team of the Center for E^{3}S concluded that pursuing different paths for the different E^{3}S research themes is the most successful approach toward the development of strong and lasting legacy programs. The different themes represent different levels of technological maturity, and they will need to evolve separately after incubation in E^{3}S. Thus far, the Center has several continuing research initiatives and programs established and/or initiated (see section IV Knowledge Transfer for details about each of the programs/initiatives):

- Berkeley Emerging Technology and Research (BETR) Center
- Negative Capacitance Industry-Supported Center
- Graphene Nanoribbons Multidisciplinary University Research Initiative (MURI)
- Semiconductor Research Corporation (SRC) JUMP Centers
- Nanophotonics NSF ERC Proposal
- E^{3}S e-Book and nanoHUB Website
- Transfer to Excellence REU Renewal Grant and Third-Party Support
- Next-Generation Transfer to Excellence (TTE-2.0) Proposal

Center Management Changes in Period 9

The E^{3}S External Advisory Board experienced one change in period 9. **Katherine Guzman** (*Sandia National Lab*) completed her five-year term with the start of this period. Dr. Guzman requested her term not to be renewed due to additional commitments at Sandia. She was thanked for her excellent service to the Center and was excused from the External Advisory Board. In addition, the appointment term of **Paolo Gargini** (*IRDS*) as chair of the E^{3}S External Advisory Board was renewed for an additional 2-year term period. Dr. Gargini accepted the renewal of his term. There are no changes of the Center's leadership and management team to report for period 9.

Table 1.2. *Center Output in Period 9*

Publications	
Peer Reviewed Journal Publications	23
Submitted for Review	6
Peer Reviewed Conference Proceedings	21
Books and Books Chapters	2
Conference Presentations	44
Other Dissemination Activities	21
Awards and Honors	13
Ph.D. and M.S. Graduates	7
Postdoc Alumni	6
Patents and Patent Disclosures	2

Summary of Plans for Period 10

Research Plans for Period 10

Research efforts in period 10 will be guided by the Strategic Research Plan (given above). Except for the replacement of **Gene Fitzgerald** with **Jeehwan Kim** (both *MIT*) at the end of period 9/beginning of period 10, no major personnel or thematic changes in the research directions of the four themes and system integration are planned in the upcoming period.

Theme I – Nanoelectronics: The nanoelectronics team consisting of the research groups of **Eli Yablonovitch** (theme leader), **Steven Louie**, **Felix Fischer**, **Ali Javey** (all *Berkeley*), **Jesus del Alamo** and **Jing Kong** (both *MIT*) will continue research efforts on the development of ultralow-energy tunnel switches from 1) traditional III-V semiconductors, 2) two-dimensional transition metal dichalcogenides, and 3) graphene nanoribbon based semiconductors.

- *III-V Nanowire TFETs:* The **del Alamo** group will continue to investigate the VNW geometry to achieve III-V transistors with steep subthreshold characteristics for both MOSFET and TFET structures with the goal achieve clear and clean single-channel electron transport. Expected major milestones are (1) the demonstration of a new mushroom-type top contact for InGaAs VNWs using selective digital etch, and (2) the in-situ sidewall etch and deposition of the MOS gate stack using a combination of thermal atomic-layer etching (TALE) and atomic layer deposition (ALD). In addition, the group will continue the collaboration with IMEC in pursuit of type-II broken-gap InAs/GaSb VNW Tunnel FETs. In period 10, it is planned to perform the entire device fabrication at MIT. Towards this goal, the group will examine TALE+ALD of the antimonide system in collaboration with University of Colorado.
- *Chalcogenide TFETs:* The **Kong** group, in collaboration with the **Javey** group, plans to synthesis large single-crystal domain TMD materials by MOCVD. In addition, the team plans to develop better transfer methods (dry, vacuum transfer) and use of high quality hBN substrate/encapsulation. In collaboration with **Yablonovitch**, the **Kong** group will also explore alternative 2D and 1D materials and structures for narrow-band metallic leads to implement steep switching. A major goal of the **Javey** group will be to visualize exciton transport in gated monolayer MoS_2. Photogenerated carriers in monolayer MoS_2 form excitons or trions depending on the concentration of background carriers, which is electrostatically controllable. Initial studies showed excitons and trions have different diffusion properties and interactions with disorder. The **Javey** group will team up with the **Bulović** group at MIT to gain a comprehensive understanding of the diffusion of different quasi-particles in these monolayers.
- *Graphene Nanoribbon TFETs:* The **Fischer** group (guided by theoretical input of the **Louie** and **Yablonovitch** groups, and device fabrication by the Bokor group) will continue to explore and expand the rational bottom-up synthesis strategy for graphene nanoribbon (GNR) tunnel junction devices. Theoretical calculations by the **Louie** group have demonstrated that in certain cases the topological interface states give rise to a narrow band at the Fermi energy that imparts metallic or semi metallic character to the GNR. The **Fischer** group will perform synthesis of such structures. In collaboration with the **Bokor** group, wet and dry transfer processes of GNRs onto insulating substrates will be developed. In addition, the **Louie** group plans to find several candidates of GNR structures with metallic narrow bands by first-principles calculations. The group will then team up with the **Yablonovitch** group on estimating the exact bandwidth needed for non-Lorentzian fast-decaying lineshapes.

Theme II – Nanomechanics: The nanomagnetics team consisting of the research groups of **Tsu-Jae King Liu**, **Junqiao Wu**, **Vladimir Stojanovic** (all *Berkeley*), **Vladimir Bulovic**, **Jeffrey Lang**, **Timothy Swager** (all *MIT*) and **David Zubia** (*UTEP*) will continue their efforts toward the theme's goal of demonstrating reliable nano-electromechanical (NEM) switch (or relay) operation below 10 mV using different approaches, including 1) coated body-biased NEM relays, 2) squeezable molecular switches ("squitches"), and 3) stretchable monolayer switches ("stritches").

- *Low-Voltage Relay Design and Integrated Circuit Operation:* In period 10, efforts by the **Liu**, **Wu** and **Stojanović** groups will focus on the ultimate goal of this project: Demonstration of reliable room-temperature operation of relay-based digital integrated circuits at 10 mV. The **Liu** group will further optimize the two-contact-dimple design ("2C" design) by incorporating a floating electrode, which should enable adjustment of the pull-in voltage. The **Wu** group will explore self-assembled molecules with different head groups and 2D materials to further reduce adhesion in NEM relays. These advances will be implemented by the **Liu** and **Stojanović** groups in their efforts to develop ultralow-voltage relay-based integrated circuit operation at 10 mV. The team will also seek a collaboration with industry partners for development of reconfigurable interconnect technology, i.e., nano-electro-mechanical (NEM) switches implemented using standard back-end-of-line (BEOL) metal wiring layers in a conventional CMOS process.
- *Squitch Project:* The **Squitch** team (the **Bulović**, **Lang** and **Swager** groups at *MIT*), in collaboration with the **Liu** group at *Berkeley*, identified four high-level research goals for period 10. The first goal is to address the remaining fabrication challenge for two- and four-terminal squitches. That challenge is to place the upper electrode above the source and drain electrodes with high yield. The second goal is to develop molecular monolayers that enable low-voltage switching over many cycles. The third goal is to build digital circuits from many squitches. Initially, wire bonding will be used to connect squitches, followed by back-side interconnects as squitch fabrication approaches 100% yield. The first circuit will be a ring oscillator. The fourth goal is to measure the dynamic performance, and explore the dynamic limits, of squitch switching. Here, the ring oscillator is enabling.
- *Stritch Project*: The inter-institutional **Stritch** team with project leader **David Zubia** (*UTEP*), the *Berkeley* research groups of **Liu**, **Javey**, and **Wu**, and the **Kong** group at *MIT* will continue to develop MEMS switches based on stretching 2D-TMDC materials. The team will study the electrical and optical properties of TMDs strained above 3% tensile strain using a new MEMS actuator design. In the current period, the group achieved 3000-fold conductivity increase in MoS_2 by straining it to 3% using a comb-drive MEMS actuator. The new design will allow horizontal stretching of the 2D materials to strains above 3%. It will also enable optical measurements simultaneously with electrical measurements.

Theme III – Nanophotonics: The nanophotonics team consisting of the research groups of **Ming Wu**, **Eli Yablonovitch**, **Constance Chang-Hasnain** (all *Berkeley*) and **Jeehwan Kim** (*MIT*) will continue research toward on-chip few-photon optical communication between electronic switches at unprecedented efficiency levels of a few hundreds of photons per bit using to concept of antenna-enhanced nanoLEDs from novel III-V heterostructures and chalcogenide materials, as well as optimized waveguide coupling.

- *Antenna-Enhanced III-V and Chalcogenide nanoLEDs:* A major goal of the antenna-enhanced nanoLED project (**Wu**, **Yablonovitch**, **Kim**, and **Javey** groups) is to demonstrate true high-speed and efficient operation of III-V devices at room temperature, and time-resolved measurements under electrical bias. The goal for the chalcogenide nanoLED project is to couple devices to antennas to enhance emission speed and efficiency. The team expects to fabricate and test antenna-coupled devices and demonstrate >50-times peak enhancement from WSe_2 LEDs in the next period. The new project on incorporating colloidal quantum dots into the antenna-LEDs (by the **Wu** group in collaboration with **Michael Bartl**) will aim to increase the selectivity of quantum dot binding to the active nanoLED region, and measuring the spontaneous emission lifetime and antenna enhancement of the spontaneous emission.
- *Coupling of nanoLEDs to Optical Waveguides:* The **Wu** and **Yablonovitch** groups will continue research on efficient coupling of the emission of antenna enhanced nanoLEDs to optical waveguides, which will be of great importance for integrated optical interconnects. Based on the simulation work

in the current period, the team will start with fabricating an electrically injected waveguide-coupled antenna-enhanced nanoLED device. On the simulation side, a simple link will first be demonstrated with a large area photodiode with the same device structure as the nanoLED. However, to create a low capacitance photodiode, the device will need to be integrated with another material. This can be achieved by coupling light from the indium phosphide waveguide to a silicon waveguide in order to route the low capacitance photodiode.

- *Integrating nanoLEDs on Silicon:* This new project will be started by the **Kim** group at MIT in close collaboration with the **Wu** and **Yablonovitch** groups at Berkeley. The **Kim** group will apply their universal technique to transfer epitaxial films of compound semiconductors to be interfaced with Si CMOS. Based on this technique epitaxial stack for the nanoLED device will first be grown on a graphene coated InP substrate, then transferred to a Si CMOS with a low-index material to help bond and define the waveguide for the nanoLED. The group aims to demonstrate (1) InP buffer layer grown on top of graphene suitable for growing the nanoLED epitaxial stacks, and (2) the feasibility of exfoliating and bonding the epitaxial buffer film on top of a Si substrate. The longer-term goal is to fabricate the antenna-enhance nanoLED on top of the transferred III-V epitaxial film with demonstration of wave-guide coupling.

Theme IV – Nanomagnetics: The nanomagnetics team consisting of the research groups of **Jeffrey Bokor**, **Sayeef Salahuddin**, **Vladimir Stojanovic** (all *Berkeley*), **Shan Wang** (*Stanford*) and **Sakhrat Khizroev** (*FIU*) will continue research toward achieving an ultra-low energy magnetic switch operating at speeds of a few picoseconds, and energy-efficient magnetic switching using spin-orbit torque and nanometer-sized spin torque transfer magnetic tunneling junction devices.

- *Picosecond Magnetic Switching and Integration with CMOS:* The goal of the **Bokor** group, in collaboration with the **Salahuddin** and **Stojanović** groups, will be to demonstrate an ultrafast magnetic memory including integrated switching using psec electrical pulses and electrical readout. Initially, the team will use the anomalous Hall effect as the electrical readout. They will also study electrical switching current as a function of the size of the magnetic dot, with the goal to switch in the range of tens of micro-Amps, the critical range, which could be delivered by a single CMOS transistor. The ultimate goal remains the integration of ultrafast magnetic switching devices on CMOS, which would be a significant legacy achievement of the Center for E^{3}S. On the system-level side, the team will explore circuit and system level experiments aimed at finding optimum ways of exploiting ultrafast magnetic switching for practical applications.
- *Spin-Orbit Torque Switching:* The **Salahuddin** and the **Wang** groups will start to leverage past E^{3}S work for energy efficient learning machines. The **Salahuddin** group will investigate Boltzmann machines, based on the demonstration that a conventional transistor coupled with a properly designed SOT magnetic tunnel junction (MTJ) device could be used to implement the stochastic units (neurons) needed for the Boltzmann machine [32]. Here the SOT is used to bias the stochastic switching of the magnet, which allows for the ‘weighting’ of the resistance seen through the MTJ. The group will work on SOT devices to reduce the current needed to deflect magnetization, which will reduce the power consumption while being used as a stochastic neuron. The **Wang** group plans to perform experiments to demonstrate SOT switching of adjacent ferromagnets, especially MTJ-compatible CoFeB and NiFe materials, in the SmB6 and heavy metal systems. Furthermore, the group plans to improve perpendicular magnetic anisotropy (PMA) of adjacent ferromagnets.
- *Magnetic Tunneling Junction Devices:* The **Khizroev** group plans to build a complete STT-MTJ device with incorporated ~2 nm $CoFe_2O_4$ nanoparticles, capable of multilevel signals, where spin polarized currents are used both for writing and reading. While a traditional STT-MTJ stack is made of two CoFeB layers separated from each other by a thin layer of MgO, the proposed STT-MTJ device will be built entirely out of Co/Pd and Co/Pt pairs. These pairs have shown a strong perpendicular anisotropy due to the surface interface. Previously, the group has demonstrated both

GMR/TMR effects and STT switching in these structures. MOKE will be used to study the multilevel signal information in the STT-MTJ devices.

System Integration: The System Integration team led by **Vladimir Stojanović** (*UC Berkeley*) will continue its important role of connecting with all four research themes in its role as “control organ”, checking that the component research outcomes and new scientific device concepts of the Center will actually lead to new energy-efficient system architectures, which enable future ultra-low power information technologies.

- *System Implementation of E^{3}S Devices:* The **System Integration** group will continue research into implementation of E^{3}S nanomechanical and nanomagnetic devices. These devices may offer the opportunity for inherent non-volatility, which may fundamentally alter the balance between computing, communication, and storage for a given application. The goal is to provide both a path to quantifying the benefits of the emerging device technologies at the circuit/system level as well as guidance to the device designers on which device design parameters are critical to improve from the system level perspective. The project aims to create modeling and optimization methodology that connects the device parameters to the circuit and system-level metrics. The plan is to develop alternative system implementations, exploiting such non-volatility across circuit, micro-architecture and architecture levels, and thus quantify the degree to which it can provide benefits in a full application.
- *Applications in Edge Computing:* In addition, the **Stojanović** group will explore integrated circuit implementations of the systems in the so-called “edge compute” scenarios since the sensory and computation functions are severely energy limited in such systems. The group has focused on hardware macros that support efficient implementations of fully connected and convolutional layers with enough re-configurability to allow mapping of various popular deep neural networks. They will introduce algorithmic modifications to allow mapping of highly irregular computations onto regular in-memory structures implemented with non-volatile memory relays and spin devices. Lastly, the recently developed E^{3}S accelerator generator framework will serve as the baseline for the generation of new designs utilizing the nanomagnetic and nanomechanical devices, as well the tool for benchmarking of their performance vs. CMOS-only designs.

Education and Diversity Plans for Period 10

In period 10, the Center will have continuity in staffing with Associate Director, **Lea Marlor** (*Berkeley*), and Diversity Director, **Kedrick Perry** (*Berkeley*), and the Center will remain committed to attracting diverse candidates to its education programs. The Education and Diversity efforts will continue receive faculty support from **Tsu-Jae King Liu** (*Berkeley*) and **Jeffrey Bokor** (*Berkeley*), in their roles as Associate Director of Education and Associate Director of Diversity, respectively.

Much of period 10 will be spent continuing to strengthen the legacy of the internship programs offered through the Center. In period 9, the Center received an NSF Site award that renewed the Transfer-to-Excellence Program for community college students. This new grant will ensure that the program will continue on even after the Center sunsets. Additional ways to strengthen the legacy of this program will continue on in period 10.

By analyzing the data on REU alumni attending graduate school and joining the Center as graduate students, we recognized that interventions were still necessary. **Kedrick Perry** led a review of the Center’s diversity strategy and identified new approaches to be adopted. These included enhancing Center awareness, targeted recruitment, strengthening minority-serving institution partnerships, and building a culture of inclusive excellence. Implementation of these strategies began in period 7 and continued throughout Period 8 and period 9. Moreover, the REU selection process for summer 2019 will continue to put greater emphasis in selecting electrical and electronics engineering undergraduates to ensure that when they successfully join one of the Center’s member institutions, the program participants will be in a department with a choice of E^{3}S faculty to serve as their advisors.

For Education, emphasis will be placed on building the legacy of the Center through a combination of online education and training materials that relate to the research themes of the Center. Videos have already been created and more are in the pipeline. Development of publicity mechanisms to target audiences is ongoing. An action plan is being generated that will include the application of assessment tools to study the efficacy of the online teaching modules, particularly the collection of mini-course modules on Energy Efficient Electronics for new Center members. Also in development is an e-book, which is geared towards a high school audience.

Knowledge Transfer Plans for Period 10

The Center for E^{3}S will continue its broad set of knowledge transfer activities, both transfer out of the Center and transfer into the Center. In particular, the Center will further extend and strengthen its activities in creating an impactful and lasting legacy while continuing its current broad knowledge transfer program.

In period 10, the launch of the E^{3}S *nanoHUB.org* website will be finalized, making educational videos available to a wide audience from high school to graduate student level. In addition, the first chapters of the E^{3}S open-access e-book on energy efficient electronics will be published. The Center will also continue to strengthen knowledge transfer from its successful educational and diversity programs, in particular, the summer research experience programs for California community college students and faculty, by publishing journal articles and conference proceedings.

Lastly, the Center plans to form a partnership with the IEEE S3S Conference (held annually in the fall in San Francisco) to ensure that the organization of the successful Berkeley Symposium on Energy Efficient Electronics Science is secured beyond the lifetime of the Center.

II. RESEARCH

1a. Goals and Objectives

The emergence of low-powered electronics for mobile internet, social networking, and cloud computing applications in recent years, has highlighted the need for energy-efficient information processing systems. The Center for E^{3}S was formed in direct response to this demand. In fact, the E^{3}S research goals and objectives are based on the recognition that the energy used to manipulate a single bit of information is currently ~100,000 times greater than the theoretical limit. From its inception, the central aim of the Center has thus been to develop an aggressive and disruptive approach to close this gap. To achieve this goal, E^{3}S seeks technological breakthroughs for two fundamental components of digital information processing systems: the communications logic switch (transistor) and the short-medium range communication of information between logic elements.

The defining research goal of the Center for E^{3}S has been guided by fundamental considerations and focuses on developing **systems operating at the minimum energy requirement for performing digital functions**. This ambitious goal is pursued by a collaborative approach, involving engineers, chemists, physicists, and materials scientists from five institutions (Berkeley, MIT, Stanford, UTEP, and FIU). The research efforts of E^{3}S are organized into four different themes: Nanoelectronics (theme I), Nanomechanics (theme II), Nanophotonics (theme III), and Nanomagnetics (theme IV). Overarching these four research themes is System Integration, leading to the common goal of new energy-efficient device architectures.

Current state-of-the-art transistors, for all their success in forging today's interconnected society, are thermally activated and thus lack the sensitivity to operate at powering voltages below ~0.7 V, even as their dimensions become smaller and smaller. Here, it should be emphasized that it is important to distinguish between the energy requirement in eV units versus the voltage requirement in "Volt" units. A bit of information on a wire represented by many electrons, must satisfy the Landauer requirement of having an energy $>>kT$, even when the voltage is $<kT/q$. For example, leading-edge CMOS technology currently dissipates a minimum of ~400,000 kT (~10,000 eV) of energy per digital function (including the energy required to charge the wires). While the ITRS Roadmap [33] projects this value to be reduced to ~40,000 kT (1,000 eV) per digital function in the year 2022, this energy value is still orders of magnitude larger than the theoretical limit of $kT\ln(2)$ or about 18 meV at room temperature, which is also referred to as the "Landauer limit" [34-36].

Given the ambitious goal of E^{3}S to develop logic systems operating at switching energies approaching the Landauer limit, Center researchers recognized early on that new types of transistors are needed with the ability to operate at significantly lower powering voltage. Figure 2.1 presents a schematic comparison of today's thermally activated conventional transistors versus the desired properties of the new type of switches pursued by E^{3}S. Switch characteristics are parameterized by sub-threshold swing, S, which represents the steepness (or sensitivity) of a switch. Here, the value of 60 mV/decade for the sub-threshold swing is equivalent to the Boltzmann factor, and is typical for thermally activated devices.

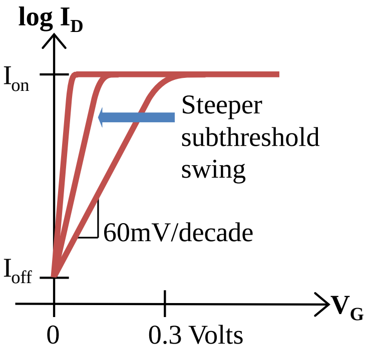


Figure 2.1. Characteristics of current (log scale) vs. voltage (linear scale) of a logic switch. In current transistors the subthreshold swing (S) is limited by the Boltzmann factor to a steepness of $\ln(10)kT/q$ = 60 mV/decade at room temperature.

From its very beginning, the Center for E^{3}S has set a more aggressive switching steepness for the proposed new switches with an ultimate goal of ~1mV/decade sub-threshold swings. Furthermore, in its search for developing a new ultra-low energy switch the Center established several key specifications that this new switch must meet, including steepness, ON/OFF conductance ratio, and current or conductance density. The values for these key specifications, which were set at the start of the Center are given below.

- Steepness (or sensitivity): ~1 mV/decade
- ON/OFF conductance ratio: 10^6:1
- Current density or conductance density (for miniaturization): 1 mS/μm

The requirement of ~1mV/decade steepness of the subthreshold swing is necessary to achieve switching at ~10mV of powering voltage. This is in stark contrast to the ~0.7 V needed in conventional, thermally activated transistors to maintain a desired ON/OFF ratio of ~10^6. Such a high ratio (i.e. low leakage current in the OFF-state) is needed since logic transistors are often at rest waiting for a signal. It should be emphasized that electrical noise in circuits is ≤1mV, good signal-to-noise ratio can be maintained even while lowering the powering voltage to 10mV. **This would result in an energy reduction factor of ~10^4 relative to today's logic circuits.**

The third requirement is conductance density ~1 milli-Siemens per μm (i.e. a 1μm device should conduct at ~1 kΩ in the ON-state) is critical for miniaturization and clock speed. For a small switch to deliver sufficient current to charge the wires in less than a clock period, today's typical requirement is a current density of one milli-Ampere per one μm of transistor size in a one-Volt circuit. Since the goal of the new switch is to lower the voltage well below 1 V, the corresponding switch conductance requirement becomes 1mS/μm rather than 1mA/μm.

In addition, the Center aims to replace some longer metal interconnects with an optical solution. The ultimate goal is to approach the quantum limit of 20 aJ/bit or 20 photons/bit as the lowest energy per bit, although 200 photons/bit would already be a major breakthrough.

1b. Table 2.1. Performance Metrics

Objective	Metrics	Frequency	Targets
Integrative Research	Multi-PI Projects	Yearly	P2: 30% P5: 75% P6: 50% P7: 60% P8-P10: 70%
	Multi-Institutional Projects	Yearly	P2: 10% P5: 30% P6: 15% P7: 20% P8-P10: 25%
	Unplanned research projects *(discontinued after period 6)*	Yearly after Period 2	P3: 1 P4: 3 P5: 0
	New joint research funding opportunities *(replaced by "New joint research funding awards"; see below)*	Beginning in Period 3	P3: 1 P4-5: 2
	Publications with authors from multiple institutions	Yearly beginning in Period 3	P3: 1 P4: 2 P5: 4 P6-P10: 5
	New joint research funding awards *(new, as replacement)*	Yearly	P6: 1 P7: 0 P8-P10: 1

No changes has been made to the metrics and metric goals as outlined in the E^3S Strategic Plan (2015-2010).

1c. Problems Encountered

In period 9, the Center faced one major problem: Stanford PI and theme IV (nanomagnetics) investigator, Prof. **H.-S. Philip Wong** left the Center for E^3S. The reason for his departure was that he took an extended leave-of-absence from Stanford to accept a high-level (vice president) position at TSMC in Taiwan. The departure of Prof. Wong left not only a hole in the nanomagnetics research theme, but as the only E^3S senior investigator at Stanford, a successor needed to be found quickly to ensure that Stanford stayed an institutional member of E^3S. After an extensive search and with input from several E^3S investigators, the Executive Committee unanimously accepted the request by nanomagnetics theme leader **Jeffrey Bokor** to replace Prof. Wong with Prof. **Shan Xiang Wang**. Prof. Wang is a faculty member in materials science and engineering and in electrical engineering at Stanford. He is an expert in magnetic materials and devices and his proposed study topological effects in magnetic switching is an excellent complimentary addition to the nanomagnetics research efforts in E^3S. After final approval by NSF program director Dr. Usha Varshney, Prof. Wang started his E^3S research program on September 1. Prof. Wang and his postdoc also participated in the E^3S Annual Retreat later that month and was officially introduced to the Center community.

All other problems encountered in period 9 have been mainly at the individual project level and not of magnitude that would require major changes in research direction or at the personnel level. The problems discussed below are typical of research programs developing new materials, fabrication processes, device structures, metrology tools, and simulation methods. Typical for a large Center, while each project is vital to the progress of a research thrust, the speed at which they proceed and the success rate can vary.

- A challenge the **del Alamo** group (*MIT*) is still facing is to find a suitable ohmic top contact for the fabrication of single-mode sub-10 nm vertical InGaAs nanowire FETs. While the group was able to produce working transistors by switching from molybdenum to nickel, the top contact is rectifying. A possible solution to this problem could be to fabricate a mushroom-type contact where the diameter of the nanowire widens at the top. The group is in the process of developing a process to implement such a top-contact design.
- The **Fischer** group (*Berkeley*) encountered problems when attempting to thermally cyclodehydrogenate nitrogen backbone doped metallic graphene nanoribbons (GNRs). They were unable to perform the required C-N bond formation step at the yields required to access defect free GNRs. In collaboration with the group of **Steven Louie** (*Berkeley*) they discovered an alternative class of metallic GNRs that do not require heteroatom doping. Synthesis of the required new molecular precursors is currently under way.
- The **Liu** and **Stojanovic** groups (both *Berkeley*) continue to face challenges in the implementation of NEM-based switches into integrated circuits. This period, the issue of device-to-device variation in native pull-in voltage (ΔV_{pi}) was identified to be a fundamental challenge for achieving sub-100 mV integrated circuit operation, since it is impractical to apply a separate body bias voltage to each relay in a large integrated circuit. Ideally, a single negative body-bias voltage should be applied for all "pull-down" relays and a single positive body-bias voltage should be applied for all "pull-up" relays. Under this scenario, the minimum circuit operating voltage (V_{DD}) would be equal to the hysteresis voltage (V_{H}) plus ΔV_{pi}. To reduce ΔV_{pi} and thereby enable smaller V_{DD}, the team currently investigates post-fabrication adjustment of V_{pi} by trapping charge on a floating electrode embedded within the gate insulating stack of a body-biased relay.
- The team of **Tsu-Jae King Liu** and **Junqiao Wu** (*Berkeley*) has discovered that ultra-low-voltage operation of NEM-based relays makes it difficult to break down native oxide formed on the contacting electrode (tungsten) surfaces, so that contact resistance increases more rapidly for ultra-

low-voltage operation. Alternative contacting electrode materials must be integrated to overcome this issue.

- Similar to last year, the **Khizroev** group (*FIU*) encountered issues with focused ion beam (FIB) system at *FIU* due to limited resolution issues. Since the instrument is crucial for fabricating sub-5-nm spin devices needed for the ongoing magnetic tunnel junction project of sandwiching nanoparticles between two magnetic layers, a student of the Khizroev group spent nine weeks in the summer in the **Bokor** group at *Berkeley* to use its superior FIB instrument. This student rotation program has proven very effective in providing students and postdocs access to needed facilities and is a great example of the collaborative nature of the Center for E^{3}S.

2a. Research Thrusts in Period 9

E^{3}S Research Strategic Plan: The strategic research plan of the Center for E^{3}S is given in the section, Context Statement, at the beginning of this Annual Report. The strategic plan has guided the research direction of the Center, and the following reporting of the research activities and progress should be viewed in the context of the Center's strategic research plan.

Center Synergy: For the current period, 18 research projects were approved by the Executive Committee and are currently conducted. All of these projects support the common goal of developing next-generation energy efficient electronics solutions. Of those research projects, 89% percent are collaborative (i.e. are joint projects between at least two senior investigator) and 72 percent are multi-institutional, connecting senior investigators from at least two different E^{3}S institutions. This is a further increase from previous years and highlights the collaborative nature across institutional borders in the Center for E^{3}S.

This collaborative nature of the Center for E^{3}S is further exemplified by a special postdoc program: The Center for E^{3}S *inter-institutional postdoc program*. Through this program, each of the four research themes hired an additional postdoctoral researcher into a joint position between at least two E^{3}S faculty members from different institutions. The *inter-institutional postdoc* is required to spend research time at the different E^{3}S institutions to increase collaborative projects and publications. This program (and associated additional spending) was approved by the executive committee in period 7 for a two-year duration. Below is a brief description of the four inter-institutional collaborations facilitated by this postdoc program:

- *Nanoelectronics*: Dr. **Valerio Adinolfi** was a postdoc shared between **Ali Javey** (*Berkeley*) and **Jing Kong** (*MIT*) for research on new chalcogenide monolayers with focus on CVD and MOCVD synthesis of 2D transition metal dichalcogenide materials and characterization of types and density of defects in these new semiconductors. Dr. Adinolfi finished his term in period 9.

- *Nanomechanics*: Dr. **Sergio Almeida** is a postdoc shared between **Tsu-Jae King Liu** (*Berkeley*) and **David Zubia** (*UTEP*) for fabrication and characterization of energy-efficient NEMS switches. The project includes the cleanroom-based development of new NEMS devices and characterization of device switching properties. Dr. Almeida will finish his term at the end of period 9.

- *Nanophotonics*: Dr. **Seth Fortuna** is a postdoc shared between **Ming Wu** (*Berkeley*) and **Eugene Fitzgerald/Jeehwan Kim** (*MIT*) for research on antenna-LED fabrication with focus on the design of new multi-layered diode structures with emission properties tailored to the enhancement characteristics of the antenna-LED architectures. Dr. Fortuna will finish his term in period 10.

- *Nanomagnetics*: Dr. **Amal El-Ghazaly** is a postdoc shared between **Jeffrey Bokor** (*Berkeley*) and **H.-S. Philip Wong/Shan Wang** (*Stanford*) for research on new magnetic devices based on ultrafast switching. The goal is to integrate ultrafast magnetic switches on top of CMOS circuits obtained from industry foundries. Dr. El-Ghazaly will continue in the Center with a UC postdoctoral fellowship.

E^{3}S Researchers: The E^{3}S collaborative research and education program has continued to bring together research groups from five academic institutions: UC Berkeley, MIT, Stanford, UTEP, and FIU:

- *UC Berkeley*: Jeffrey Bokor, Constance Chang-Hasnain, Felix Fischer, Ali Javey, Tsu-Jae King Liu, Steven Louie, Sayeef Salahuddin, Vladimir Stojanovic, Junqiao Wu, Ming C. Wu, and Eli Yablonovitch.
- *MIT*: Vladimir Bulovic, Jesus del Alamo, Eugene Fitzgerald (will phase out by end of period 9), Jeehwan Kim (will join Center in period 9), Jing Kong, Jeffrey Lang, and Timothy Swager
- *Stanford*: H.-S. Philip Wong (left Center July 1), Shan Wang (joined Center September 1)
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

The participation of all senior researchers (faculty) within the Center's main research themes is give in the table below. As discussed above, **H.-S. Philip Wong** (*Stanford*) left the Center effective July 1, 2018. He was replaced by **Shan Wang** (*Stanford*). In addition, **Gene Fitzgerald** (*MIT*) will phase out of the Center by the end of period 9 due to extensive commitments at a research lab in Singapore. **Jeehwan Kim** (*MIT*) will take over Fitzgerald's semiconductor growth facility at MIT and will continue the nano-LED growth project for theme III (nanophotonics). Lastly, note that **Vladimir Stojanovic** (*Berkeley*) leads the system integration efforts of the Center and collaborates with all four themes.

Table 2.2. Faculty Participation by Theme in Period 9

Institution	Faculty	Theme I	Theme II	Theme III	Theme IV
UC Berkeley	Bokor				x*
	Chang-Hasnain			x	
	Fischer	x			
	Javey	x		x	
	King Liu		x*		
	Louie	x			
	Salahuddin				x
	Stojanovic	x	x	x	x
	J. Wu		x		
	M. Wu			x*	
	Yablonovitch	x*		x	
MIT	Bulovic		x		
	del Alamo	x			
	Fitzgerald[1]			x	
	Kim[2]			x	
	Kong	x			
	Lang		x		
	Swager		x		
Stanford	Wong[3]				x
	Wang[4]				x
UTEP	Zubia		x		
FIU	Khizroev				x

Legend: x* denotes theme leader; [1]denotes phasing out of Center; [2]denotes phasing into Center; [3]left Center on July 1, 2018; [4]joined Center on September 1, 2018

2ai. Theme I: Nanoelectronics *Theme Leader:* **Eli Yablonovitch** *(UC Berkeley)*

The aim of the nanoelectronics theme is to develop a logic switch that is orders-of-magnitude more energy efficient than the conventional transistors. The ultimate goal is a solid-state switch that exhibits high ON/OFF ratios, steep modulation, high conductance (current) densities, and that can be actuated in the ~10 milli-Volt range.

For such an ultralow-voltage switching device, the tunnel switching mechanism appears to be inevitable since tunneling is an unavoidable physical effect of the ongoing miniaturization of devices [1]. In particular, tunnel switches operating by the density-of-states modulation mechanism (also called the "energy filtering mechanism") appear to be highly promising as they projects high conductance in the ON-state [2, 3]. However, experimental research failed to yield devices that approach the predicted and hoped-for performance. The main reason for underperformance of current tunnel transistors is that they operate by the tunnel-distance modulation mechanism. While they show good steepness at low current densities [4-7], they are rather ineffective at high conductance (current) density needed for high clock speed. When averaged over both low and high current densities, only a ~50 percent reduction in operating voltage might be achievable, (at best 250 mV), compared to today's conventional transistors.

Initial research efforts at E^3S aimed at elucidating why previous attempts to fabricate density-of-states modulation switches have failed. Guided by theme-leader **Eli Yablonovitch** (*Berkeley*), E^3S nanoelectronics researchers discovered that the density-of-states modulation mechanism demands higher materials interface perfection than ever previously required and achieved in solid-state electronics. The reason for this is that tunneling probability, which is proportional to the two-dimensional density of quantum states, needs to compete with the bandgap defect density of states—a very important figure-of-merit in electronics science. Unfortunately, even in the most favorable material systems (Si/SiO_2 interfaces) [37], after decades of research, the defect density does not fully meet the requirements.

In response to this important discovery, the Center has focused on both searching for new material systems with ultra-low interfacial defect states and fully understanding interfacial effects and trap-assisted tunneling. The **del Alamo** group (*MIT*) uses III-V vertical nanowire TFET structures as model systems [2, 3] to study interfacial effects and trap-assisted tunneling, and other non-idealities of tunnel transistors in collaboration with the **Yablonovitch** group. The goal is to discover the ultimate performance potential of tunnel transistors by performing current-voltage spectroscopy of single trap nanowire tunneling. In addition, **Yablonovitch** is addressing the question of the fundamental spectroscopic sharpness of tunneling energy levels, with the emphasis on the spectral wings, which determine ON/OFF ratio.

Regarding the search for new semiconductor materials with ultra-low interfacial defect states the Center investigates two different systems: Two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs). The **Javey** group at Berkeley and the **Kong** group at MIT develop new bottom-up synthesis methods for 2D-TMDCs, which are single-layer, fully covalently bonded structures with minimum surface roughness and low density of dangling bonds. Semiconducting GNRs, on the other hand, are chemically synthesized by organic chemist **Felix Fischer** (*Berkeley*) in an atom-by-atom fashion. Due to the fully controlled synthesis, the electronic properties of GNRs can be precisely tailored, including quantum tunneling herterostructures with built-in molecular quantum dots. The experimental aspects of this project are supported by theoretical electronic structure calculation by physicist **Steven Louie** and guidance by **Eli Yablonovitch** (both *Berkeley*).

The following provides details of period 9 research efforts in the nanoelectronics theme on:

Ia. Vertical Nanowire TFETs
Ib. Spectroscopic Line-Shape of Tunneling Energy Levels
Ic. Layered Chalcogenide TFETs
Id. Graphene Nanoribbon Quantum Tunneling Structures

Ia. Vertical Nanowire TFETs

The goal of this project has remained the demonstration of single-channel III-V vertical nanowire TFETs with steep subthreshold characteristics. In recent years, the **del Alamo** group (*MIT*) has shown that vertical nanowire III-V TFET structures are excellent model systems to study the underlying physics of tunneling in semiconductors, while revealing the issue of defect assisted tunneling in the OFF-state [3]. The vertical nanowire geometry is fabricated by a top-down approach, in contrast to most efforts around the world that are pursuing a bottom-up approach (via nanowire epitaxial growth), which is less flexible. The **del Alamo** group has developed very high aspect ratio nanometer-scale etching technology and a new rapid thermal annealing (RTA) step capable of reaching sub-10 nm diameters [2, 15, 16]—the first vertical nanowire transistors of any kind on any semiconductor system with diameters below 10 nm.

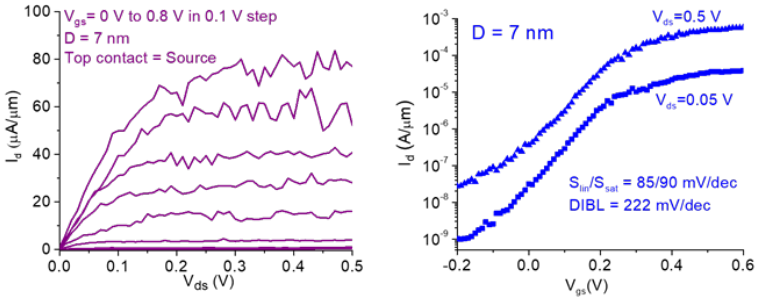


Figure 2.2. I-V characteristics and subthreshold behavior of vertical nanowire MOSFETs with 7 nm diameter.

In period 9, **del Alamo** group succeeded in fabricating working InGaAs VNW MOSFETs with record nanowire diameter down to 7 nm (Figure 2.2), the target diameter for a future VNW III-V CMOS technology and a regime in which prominent single-channel electron transport is to be expected [17]. This latest result was enabled by the recently developed solvent-based digital etch technique and the use of alloyed Ni contacts (as opposed to non-alloyed Mo contacts). It was found that transistors based on Mo top contact open up at a diameter around ~15 nm, while Ni contacts remained conducting down to diameters of 7 nm [18]. Importantly, whereas well-saturated transistor output characteristics, as shown in Figure 2.2 are obtained only by placing the source at the top of the nanowire. If the source is at the nanowire bottom and drain at the top, the device exhibits Schottky-like unsaturated characteristics. Also, it should be emphasized that device currents are rather small indicating that there is still a need for further improvement of the top contact. In fact, a detailed analysis of the fabricated devices revealed several avenues for mitigation of parasitic effects and improving the device characteristics, including improved top contact design and sidewall interface defect control. These improvements will be critical on the way to isolate and study the unique physics associated with single-channel transport, as predicted by the **Yablonovitch** group's modeling work on single 1D subband devices.

The **del Alamo** group reported a second significant milestone in period 9, which resulted from a collaboration with the group of Steven George (*University of Colorado, Boulder*). In detail, they developed a thermal atomic layer etching (TALE) method for InGaAs and InAlAs and demonstrated InGaAs FinFETs through *in-situ* TALE and atomic layer deposition (ALD) of the gate oxide [19]. This constitutes the first transistor demonstration fabricated by *in-situ* TALE+ALD of any kind on any material system. The big advantage of this method is a greatly increased interface quality control, as illustrated in the sharp oxide-semiconductor interface revealed by transmission electron microscopy (TEM) imaging (Figure 2.3). Extremely thin fins down to 3 nm in width have been demonstrated. Further, TALE has been shown to etch InAlAs faster than InGaAs and it is then possible to fabricate suspended fins with the gate stack all around

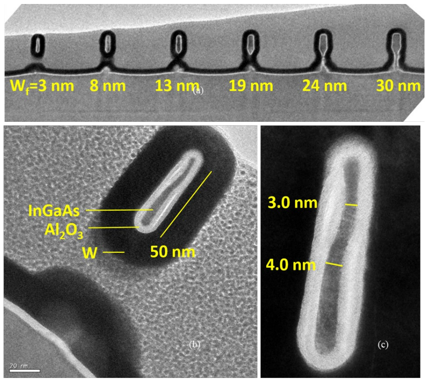


Figure 2.3. TEM images of InGaAs/InAlAs fins on top of an InP substrate fabricated by TALE+ALD.

(bottom images in Figure 2.3). The group also fabricated InGaAs FinFETs using this new *in-situ* TALE+ALD technique. Devices with fins as thin as 2.5 nm were fully functional, as shown in the electrical characteristics in Figure 2.4. The resulting devices have far better ON- and OFF-state characteristics than similar devices fabricated by conventional techniques. This opens new avenues for the fabrication of TFETs with vastly improved interface characteristics.

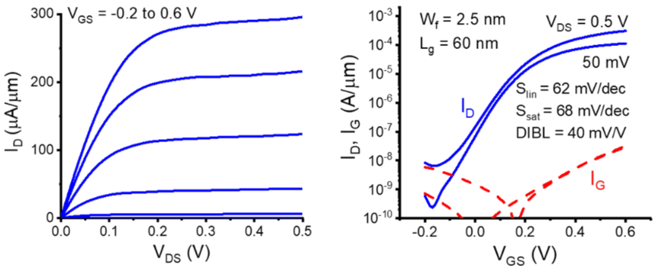
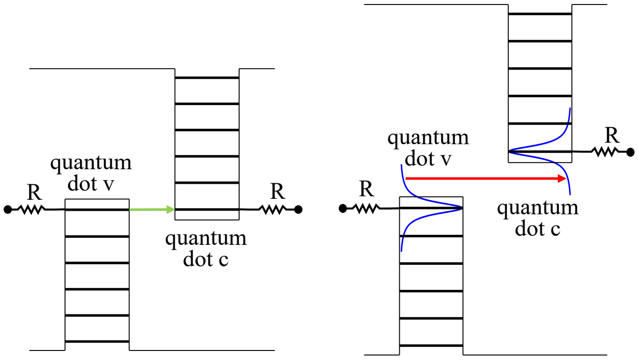


Figure 2.4. I-V characteristics and subthreshold behavior of InGaAs FinFETs with 2.5 nm fins, fabricated by the new *in-situ* TALE+ALD technique.

Ib. Line-Shape Physics for Tunnel Transistors:

The preferred energy filtering mechanism for tunnel transistors relies upon the quantum level energy alignment. This is illustrated in Figure 2.5. Here, a) represents the ON-state and b) represents the OFF-state of the topmost valence band quantum well level and the bottom-most conduction band quantum well level. Thus, the ON/OFF ratio depends on the shape of the spectral tails of the energy levels. The steepness of the spectral tails translates directly into steepness and sensitivity of the tunnel transistor response.

The most fundamental line broadening mechanism is the interaction of a sharp quantum dot energy level with the contact wires as illustrated in Figure 2.5. Therefore, the tunneling itself leads to a spectral broadening whose lineshape, has not yet been measured. Measurement of the spectral shape of energy levels, by current-voltage spectroscopy, is a near term goal of **del Alamo**'s work. With regard to the expected spectral shape of an energy level, of the quantum dot energy level for example, the common physics model is the famous Lorentzian line-shape: $1/[(\omega-\omega_o)^2+(1/\tau)^2]$. While a Lorentzian spectral shape is often assumed, it presents a problem for tunnel transistors. Since the spectral wings of a Lorentzian fall very slowly from line center, (red curve in Figure 2.6a), it becomes difficult to turn the transistor off, and to achieve the required 10^6:1 ON/OFF ratio.



(a) aligned

(b) misaligned

Figure 2.5. The principle behind the energy filtering mechanism for tunnel-Field Effect Transistors (tFET). (The gate electrode not shown) (a) The topmost valence band energy level, of a small area quantum well, aligns with the bottom-most conduction band energy level, allowing current to pass, (green arrow). (b) An attempt to switch the device off. Owing to the spectral tails of the respective energy levels, current continues to leak from valence to conduction band.

Fortunately, the Lorentzian line-shape is only an approximation. The Lorentzian power spectrum, is the Fourier transform of the following wave-function auto-correlation function: $\langle\psi(0)\psi(t)\rangle\sim\exp\{-t/\tau\}$. The exponential decay would arise, for example, from Fermi's Golden Rule. This is known to be only a perturbation theory estimate. At early times, the decay of coherence is known to be parabolic, which gradually evolves into an exponential time decay at later times. The slow parabolic decay at very short times eliminates the wide spectral wings of the Lorentzian, and leads to a proper sharp exponential spectral decay away from line-center.

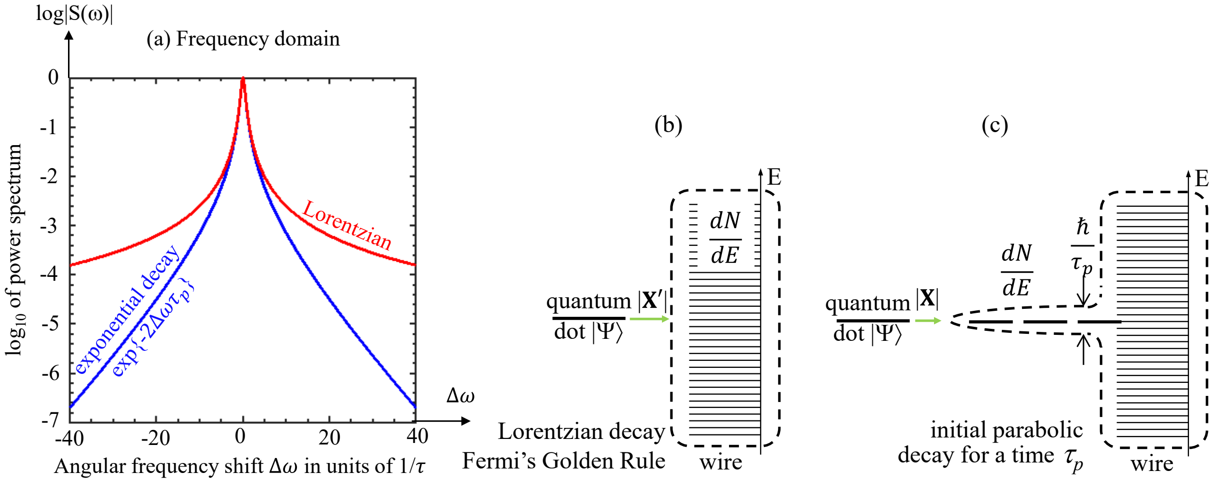


Figure 2.6. (a) The temporal decay in time can be either exponential from the earliest times (red), or have an initial parabolic decay period $2\tau_p$, before exponentially decaying with a time constant 2τ, (blue). The corresponding spectra: a broad Lorentzian (red), exponential spectral tails (blue). (b) A quantum dot coupled to a wire with a broad continuum density of states *dN/dE* giving rise to the red Lorentzian curve. (c) A quantum dot coupled to a wire with a narrow density of states *dN/dE*=$\hbar/\tau_p$giving rise to the blue exponential spectral tails.

The **Yablonovitch** group identified sample decay curves that behave correctly, such as $\langle\psi(0)\psi(t)\rangle \sim \exp\{-\sqrt{[b^2+(t/\tau)^2]}\}$, which are exponential at long times, but parabolic at short times, controlled by the dimensionless parabolic parameter "b". The corresponding spectral line-shape is illustrated as the blue curve in Figures 2.6a. The general requirement is an initial temporal parabolic falloff, which then leads to the desirable exponential wings to the spectrum. The distinction between the red and blue spectra of Figure 2.6a, is illustrated by Figure 2.6b (red) or Figure 2.6c (blue). The desirable situation is Figure 2.6c, where instead of tunneling to a wide continuum of states, the initial coupling is toward a narrower state density, $\hbar/\tau_p$ which later couples to the wide state density of a metal. The time τ_p is the duration of the initial parabolic time period, before exponential decay sets in.

This is a new form of spectral line-shape theory, specializing on the far wings of the spectrum, which has received insufficient scientific attention. There are various decoherence mechanisms belonging to different scientific domains. We are very interested in spectral tails associated with tunnel broadening, but there are similar considerations that are needed for spontaneous light emission, and for phonon induced broadening, which commonly arises in condensed matter. What all these

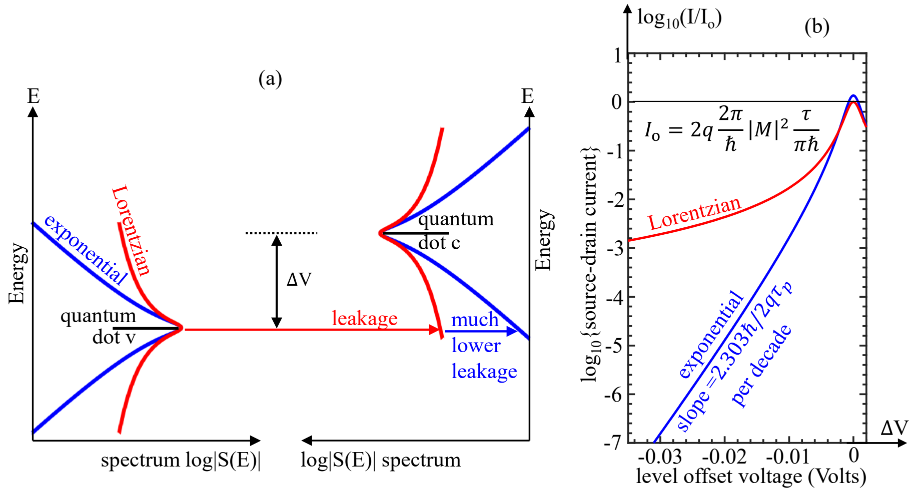


Figure 2.7. (a) Lorentzian spectral line-shapes lead to unacceptable off-state leakage, blue versus red curve. (b) The corresponding current/voltage curves showing the preferred sub-threshold swing = $2.303\hbar/2q\tau_p$ only for the blue curve.

scientific domains have in common is that the Lorentzian approximation breaks down in the spectral wings where there has been insufficient experimental and theoretical knowledge.

The net consequence of this new understanding of spectral line-shapes is that when the quantum levels are offset by voltage ΔV as in Figure 2.7a, the off-state leakage is greatly reduced owing to the exponential falling, non-Lorentzian, spectral tails (blue). This projects to the proper turnoff in the current/voltage curves in Figure 2.7b. The excellent sub-threshold slope is controlled by the parabolic initial decay period τ_p. Thus, we define a recipe for controlling spectral line-shapes, which translates directly to the preferred current/voltage curves for the future of electronics.

Ic. Layered Chalcogenide TFETs

The E^3S nanoelectronics theme recognized early on the excellent potential of two-dimensional transition metal dichalcogenides (2D-TMDCs) for TFETs operating on the desired energy filtering mechanism. In principle, 2D-TMDCs have a completely covalently bonded structure, minimum surface roughness, and low density of dangling bonds or surface defects in their monolayers. In fact, the group of **Ali Javey** (*Berkeley*) demonstrated practically functioning TFETs from 2D materials [38]. However, the **Javey** and **Yablonovitch** groups soon realized that a sharp subthreshold swing employing the preferred energy filtering switching scheme requires sharp conduction/valence band edges with very little to no tail states. This can only be achieved by highest quality 2D chalcogenide materials, and as a result, E^3S 2D chalcogenide research efforts focused on both the development of new synthesis methods for large-area, uniform 2D-TMDCs (spearheaded by the group of **Jing Kong** at *MIT*) and the post-synthesis treatment of 2D-TMDC materials to optimize their properties (led by the **Javey** group).

In the last reporting period, the **Kong** group started to use MOCVD for the growth of large area 2D chalcogenide monolayers. In this period, growth efforts have intensified and successful growth of monolayer MoS_2 has been demonstrated on a Si/SiO_2 substrate at 340 °C (furnace temperature of 750 °C) with a measured field effect mobility of ~45cm^2/Vsec. Interestingly, MoS_2 grown with MOCVD at higher temperatures displayed lower mobility values. Current studies are aimed at understanding the reason behind these observations.

In parallel, the **Kong** group has also succeeded in the synthesis of the 2D monolayer semimetals TiS_2 and VS_2 by ambient pressure chemical vapor deposition (CVD). Using *in-situ*-generated titanium chloride gaseous precursor, the group was able to grow large-area, highly crystalline 2D TiS_2 nanosheets (Figure 2.8). The addition of ammonium chloride promoter reacts with titanium powders and switches the solid-phase sulfurization reaction into a CVD process, thus providing great controllability over the size, shape, and thickness of the TiS_2 nanosheets [39]. This method opens a new avenue for the CVD growth of moisture- and oxygen-sensitive 2D chalcogenides directly from metal powders and paves the way for exploring their intriguing properties and applications.

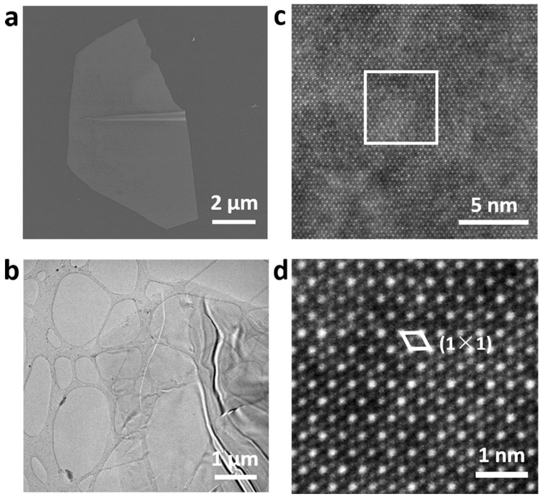


Figure 2.8. a) SEM image of a TiS_2 nanosheet on SiO_2/Si. Large field-of-view TEM image (b) and HAADF-STEM images (c, d) of TiS_2 nanosheets.

The **Kong** group also developed a two-step CVD strategy that enables the synthesis of solely TMD-made semimetal-semiconductor lateral heterostructures (i.e. MoS_2-VS_2 stitches). Specifically, semimetal VS_2 flakes were first synthesized followed by the synthesis of semiconducting monolayer MoS_2 on the same substrate. Remarkably, in such heterostructures, MoS_2 was found to nucleate from the vertexes of multilayered VS_2 flake and evolve into a polycrystalline monolayer film surrounding the VS_2 flake. Compared to the lithography and lift-off processes required for fabricating metal-semiconductor contacts in silicon technology, direct synthesis of such lateral heterostructures enables straightforward fabrication of all-TMD-based electronics with atomic thickness. The transistors fabricated with solely TMD-made metal-semiconductor contacts exhibited contact resistance as low as 500 $\Omega\cdot\mu m$, which is two orders of magnitude lower than that previous reports for polycrystalline monolayer MoS_2 [20].

Complimentary to the growth efforts in the **Kong** group, the group of **Ali Javey** has focused on 2D material engineering in order to realize better device performance through material quality improvements. In recent years, several breakthroughs were achieved, including a superacid treatment method that “heals” defects in 2D chalcogenides [40, 41], and using photoluminescence lifetime and quantum yield efficiency to fully characterize and understand edge-recombination in 2D chalcogenide materials [42]. In period 9, the **Javey** group succeeded in directly measuring the edge recombination velocity (ERV) of several few-layer TMDC materials by scanning probe lithography (SPL) patterning. The various parameters such as voltage bias, amplitude setpoint, and humidity that effect SPL of 2D materials were analyzed and tuned to reach sub-100 nm resolution. Patterned 2D MoS_2, $MoSe_2$, WS_2, and WSe_2 materials had measured ERVs of 2.0×10^4 cm/s, 2.6×10^3 cm/s, 1.8×10^4 cm/s, and 1.1×10^4 cm/s, respectively. The large variations in measured ERVs highlights the utility of SPL utilized towards understanding material dependent TMD edge defects.

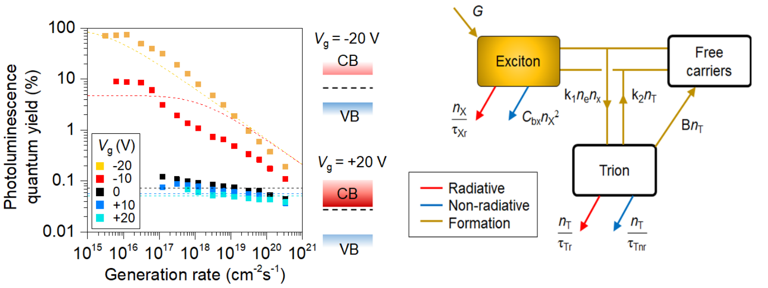


Figure 2.9. Near-unity PLQY in MoS_2 by electrostatic doping and the recombination model. **Left:** PLQY vs generation rate plot in MoS_2. Dashed lines show the fitting curve from the model. **Right:** Details of the optical processes of TMDC materials under gate bias.

In addition, the **Javey** group gained new insights into radiative processes in 2D-TMDCs. The group demonstrated that the photoluminescence quantum yield (PLQY) of as-exfoliated MoS_2 and WS_2 monolayers reaches near unity when the monolayers are made almost intrinsic by electrostatic doping, without any chemical treatment (Figure 2.9, left). This result reveals that, even in the presence of defects in sulfur-based TMDCs, neutral exciton recombination can be entirely radiative. The group also proposed a kinetic model to explain the photophysics of both sulfur- and selenide-based TMDC monolayers (Figure 2.9, right). Finally, they showed that the most effective chemical passivation technique for 2D-TMDC monolayers, a treatment with bis(trifluoromethane)sulfonamide (TFSI), is predominantly electron counter-doping.

Id. Graphene Nanoribbon Quantum Tunneling Structures

The graphene nanoribbon (GNR) project is the youngest of the nanoelectronics theme research projects. However, since its start in period 5 of the Center, it has made tremendous progress in synthesizing novel materials systems capable of producing the most perfect molecular scale device structures—a pre-requisite for future progress in ultra-low voltage switching. GNRs are top-down synthesized polymeric structures that promise atomic precision and low defect density. In addition, GNRs are semiconductors, which distinctly differentiates them from graphene itself, which is a semimetal. The semiconducting property arises from lateral electron quantum-confinement effects in the one-dimensional nanoribbon structure. In period 9, the group of organic chemist **Felix Fischer** has continued to lead the experimental aspects of this project. Broad theory support is provided by **Eli Yablonovitch** and the group of theoretical physicist **Steven Louie**, who brings extensive expertise in *ab initio* calculations of electronic structures for the design of future semiconductors into the nanoelectronics theme. In addition, the group of **Jeffrey Bokor** is working closely with this team and provides guidance in integrating GNRs into FET device architectures.

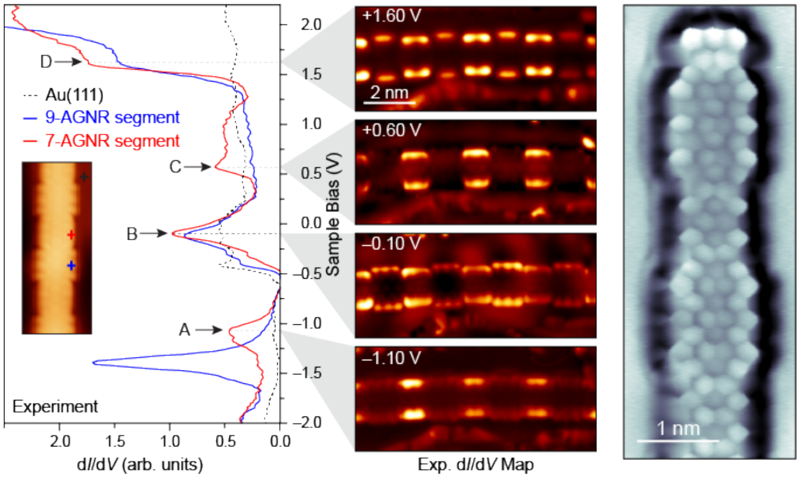


Figure 2.10. Experimental dI/dV spectra (**left**) and maps (**middle**) at energies corresponding to the symmetry protected topological states of a 7/9-armchair-GNR. **Right:** Atomically resolved STM image of a superlattice of symmetry protected topological states in 7/9-armchair-GNRs.

In this period, the **Fischer** group, in close collaboration and with theoretical support by the **Louie** group, has successfully demonstrated that symmetry protected topological states can be rationally engineered into bottom-up synthesized GNRs [21]. This discovery presented an entirely new route to band engineering in monolayer materials based on precise control of their electronic topology. The **Louie**'s group theoretical work had predicted the existence of 1D symmetry-protected topological phases in GNRs [22]. The **Fischer** group then successfully demonstrated for the first time the rational design and experimental realization of a topologically engineered GNR superlattice that hosts a 1D array of topological states, thus generating otherwise inaccessible electronic structures (Figure 2.10). This strategy also enables new end states to be engineered directly into the termini of the 1D GNR superlattice. The atomically precise topological GNR superlattices were synthesized from molecular precursors on a Au(111) surface under ultra-high vacuum (UHV) conditions and characterized by low temperature scanning tunneling microscopy (STM) and spectroscopy (STS) as shown in Figure 2.10. The experimental results and first-principles calculations revealed that the frontier band structure of these GNR superlattices is defined purely by the coupling between adjacent topological interface states. This represents an entirely new strategy to access metallic states and unusually sharp energy levels ($\Delta E \sim 5$ meV), which the **Yablonovitch** group has recently identified as critical for the successful realization of TFET architectures.

In the last period, the E^{3}S GNR nanoelectronics group identified the development of GNRs with a metallic band structure (VB/CB overlap ~ 0.1 eV) as high priority. Such metallic GNRs are essential for TFET device structures since they would serve as conductive leads to contact the functional element of a graphene based tunneling FET by overcoming contact resistance between a semiconducting GNR device and a macroscopic metal contact. In response to this challenge, the **Louie** group identified several synthesizable metallic GNR structure, such as a nitrogen-doped armchair GNR (AGNR), and cove-edged GNRs with even rows of carbon atoms in the width direction and in a staggered edge configuration [43]. The group used density functional theory (DFT) calculation to obtain the band structure of cove-edged GNRs with different widths. They discovered that when there are even number rows of carbon atom in the width direction, a family of cove-edged GNRs where the carbon vacancy and hexagonal carbon ring on both edge has a staggered configuration are metallic. Using these theoretical results, the **Fischer** group successfully prepared a series of GNR molecular precursors and was able to polymerize them on the surface. The critical cyclodehydrogenation step however did not proceed at practical temperatures and they were only able to observe fragmentation at T > 400 °C. In consultation with the **Louie** group, the target structure was reevaluated and an alternative new design based on a more traditional and more robust surface reaction process was developed. The synthesis of this new class of GNRs is ongoing and it is expected that the monomer synthesis will be completed by the end of period 9.

2aii. *Theme II: Nanomechanics* *Theme Leader:* **Tsu-Jae King Liu** *(Berkeley)*

The nanomechanics theme investigates ultra-low-voltage switches based on nano-electro-mechanical (NEM) actuation. In principle, mechanical switches (or relays) only conduct current when two conductive electrodes are in contact, and prevent current when these electrodes are physically separated. In fact, NEM switches can achieve immeasurably low off-state leakage (I_{OFF}) and abrupt switching behavior across a wide range of temperatures [8] and hence can be operated with much lower voltage than can any transistor. NEM actuation-based switches are therefore of keen interest for digital integrated circuit applications for which energy efficiency is paramount. A prime example is wirelessly networked devices in the emerging Internet of Things (IoT).

Although mechanical relays switch more slowly than do transistors, circuit design co-optimization to minimize the number of mechanical switching delays per function can compensate for this [44]. The nanomechanics theme has collaborated closely with the E^{3}S System Integration team to develop strategies for improving both overall system performance and energy efficiency by leveraging zero-leakage NEM switches.

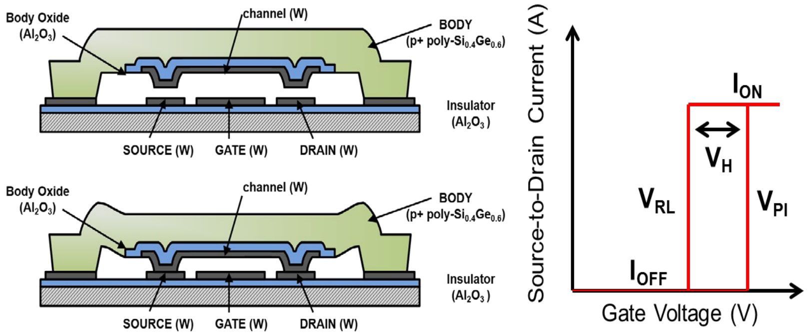


Figure 2.11. Left: Schematic illustration (cross-sectional view) of a NEM switch in the OFF state (upper) and in the ON state (lower). **Right:** Corresponding current-voltage plot, showing pull-in voltage (V_{PI}), release voltage (V_{RL}) and hysteresis voltage (V_H).

In recent years, the nanomechanics team identified contact stiction as a main challenge and thus has focused on finding approaches to reduce or eliminate this phenomenon. Contact stiction gives rise to hysteretic switching behavior; that is, the gate voltage at which the switch turns OFF (*i.e.*, the release voltage, V_{RL}) is smaller than the gate voltage at which it turned ON (*i.e.*, the pull-in voltage, V_{PI}). The hysteresis voltage ($V_H = |V_{PI} - V_{RL}|$) limits reduction in the operating voltage (V_{DD}) and hence the switching energy of a NEM switch. E^{3}S researchers have developed several new approaches to avoid contact stiction, including the "squitch" concept – invented at *MIT* – in which a molecular layer is sandwiched between the two conductive electrodes to prevent direct contact. A tunneling current is then modulated by using electrostatic force to squeeze the molecular layer. A complementary "stritch" concept – invented at *UTEP* – uses electrostatic force to stretch (rather than to squeeze) a two-dimensional molecular layer suspended between the two conductive electrodes, in order to induce a phase change and thereby modulate the current.

The "squitch" project has been pursued by the *MIT* groups of **Vladimir Bulović**, **Jeffrey Lang** and **Timothy Swager** in collaboration with the groups of **Tsu-Jae King Liu**, **Junqiao Wu**, and **Vladimir Stojanović** at *Berkeley*. The goal is to insert molecular layers between conductive electrodes in body-biased relays (Figure 2.11). This approach should also enable ultra-low-voltage operation with high device yield for relay-based integrated circuit demonstrations. In addition, the **Liu** group collaborates with the group of **David Zubia** at *UTEP* to fabricate MEM actuators for the "stritch" project.

The following provides details of period 9 research efforts in the nanomechanics theme on:

IIa. Ultra-Low-Voltage Relay Design and Operation
IIb. Sub-100 mV Relay-Based Digital Integrated Circuits
IIc. Squitch: Molecular Squeeze-Switch
IId. Stritch: 2D Chalcogenide Stretch-Switch

IIa. Ultra-Low-Voltage Relay Design and Operation

Under the guidance of theme leader **Tsu-Jae King Liu**, research efforts in period 9 focused on further improvements of the NEM relay design and low-voltage operation. The team identified several key scientific challenges toward demonstration of reliable operation of relay-based digital integrated circuits (ICs) at voltages below 100 mV—one of the major goals of the nanomechanics theme.

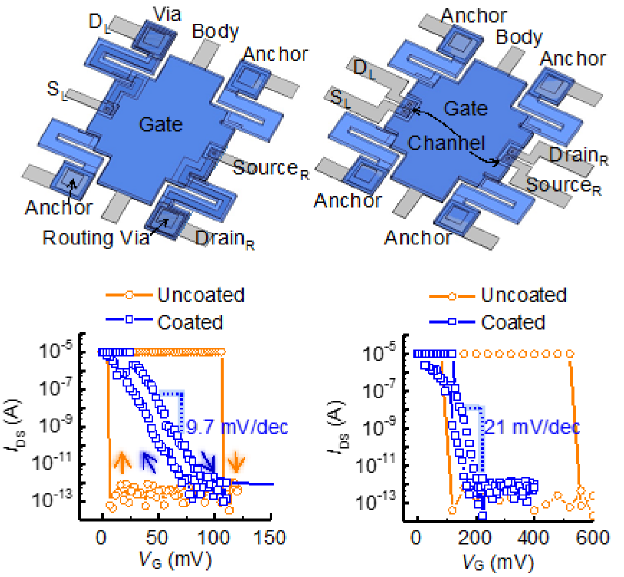


Figure 2.12. Top: Schematic views of the two-contact (2C) relay design (**left**) and the old four-contact (4C) relay design (**right**). **Bottom:** I_{DS}-V_G curves for 2C relays (**left**) and 4C relays (**right**) in P-relay operation, with and without PFOTES coating, measured at 300 K and 10 μTorr. V_{DS} = 200 mV; $|V_B|$ = ~15 V. The current compliance is set to limit I_{DS} to 10 μA.

These challenges include the reduction of both relay switching hysteresis voltage (V_H) and subthreshold swing, and the device contact reliability/endurance at ultra-low-voltage operation. To address the challenge of minimizing V_H, improvements in relay design were explored and the effects of various anti-stiction coatings on relay switching characteristics were compared. The **Liu** group developed an improved body-biased relay design for reducing contact stiction. In detail, the previous relay design with four contact dimples ("4C" design) used a conductive channel layer (attached underneath the gate electrode with an intermediary insulating layer) to form a bridge between a pair of source and drain electrodes (formed from the same layer as the body electrode) in the ON state. The new relay design ("2C" design) has only two contact dimples (one for each electrical switch) for smaller total contact area and hence lower adhesion force (F_{AD}) as well as lower ON-state resistance (R_{ON}) [23]. Both the 2C and 4C MEM relay design schematics are compared in Figure 2.12 (top). The fabrication process was modified and a new test chip was designed to enable comparison of the old relay design with the improved relay design; to use the improved relay design in integrated circuits; and to improve the relay interconnection scheme using tungsten (the channel layer) rather than doped polycrystalline silicon-germanium (the structural layer) to form cross-over connections. Figure 2.12 (bottom) compares the I_{DS}-V_G characteristics for the new 2C and the old 4C relays. Results are summarized in Figure 2.13. They reveal that V_H is lower for the 2C devices compared to 4C, and it also much lower for relays coated with an anti-stiction layer of PFOTES (perfluorooctyltriethoxysilane) molecules due to reduced surface adhesion energy between contacting electrode surfaces. The subthreshold swing (SS) is approximately twice as large for the 4C design compared to the 2C design, since twice as much force is needed to compress the PFOTES molecules in a 4C relay.

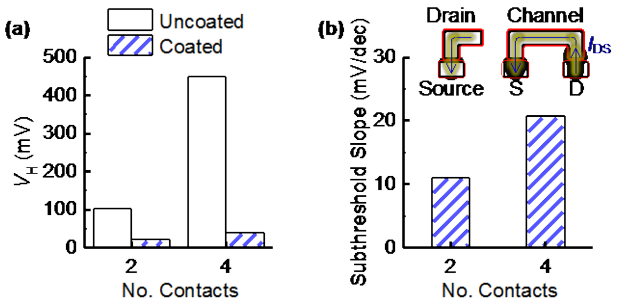


Figure 2.13. Comparison between (a) average hysteresis voltage (V_H) values and (b) average subthreshold slope (SS) values for 2C and 4C relays, with and without PFOTES coating, measured at 300 K and 10 μTorr; V_{DS} = 200 mV; $|V_B|$ = ~15 V.

To further reduce surface adhesion of NEM switches without degrading their conduction, and thereby further improve V_H and SS device characteristics, the group of **Junqiao Wu** (*Berkeley*) joined forces with the **Liu** group and investigated new anti-stiction surface coating molecules. They systematically investigated self-assembled molecular coatings with various chain lengths and found out that to reduce adhesion, more CF_2 molecules must be added to the chain, however, this would degrade conduction as the self-assembled molecular coating is insulating. It was found that this trade-off between adhesion and conduction could be overcome by using self-assembled molecular coatings with branched tails. With this approach, relays with V_H as low as 20 mV with abrupt switching were achieved. Best results were obtained from the branched self-assembled molecular coating perfluoro(2,3-dimethylbutan-2-ol). This molecule has ~ 24 fluorine atoms per nm and hence is very effective in reducing adhesion. In addition, the perfluoro molecule is less than 0.5 nm long and as such does not degrade conduction substantially. A 62% reduction in hysteresis and 52% reduction in average switching slope was achieved without affecting the instantaneous switching slope. Compared to PFOTES, the new perfluoro molecule has more than twice fluorine atoms/nm, while its length is only about 1/3 that of PFOTES. Currently, work is underway to use this new anti-stiction coating with 2C relays and relay-based ICs.

IIb. Sub-100 mV Relay-Based Digital Integrated Circuits

The **Liu** group has continued their collaborative work with the group of **Vladimir Stojanović** (*Berkeley*) toward the goal of demonstrating reliable operation of relay-based digital integrated circuits (ICs) at voltages below 100 mV. With the significant NEM relay improvements of the 2C design described in section IIa and the application of optimized anti-stiction coatings, the team achieved a major milestone in this funding period: reliable room-temperature operation of a variety of relay integrated circuits at a voltage of 50 mV. No other digital integrated circuit device technology developed to date has even been projected to be able to operate at such low voltages. Various two-input logic functions have been implemented with only two relays using pass-gate circuit topology. Figure 2.14 illustrates the correct operation for NOT, AND, OR, and XOR logic gates, all functioning at 50-mV operating voltage [24].

The **Liu** and **Stojanović** team also showed that pass-gate circuit topology minimizes the number of mechanical delays and the number of relays per digital function [25]. In Figure 2.15, a 2:1 multiplexer (MUX) is demonstrated using only two relays; for comparison, a CMOS implementation requires at least four transistors. The source electrode of each relay acts as an input signal line; the gates are connected together to form a select line; and the drain electrodes form interconnects at the output node. The voltage waveforms confirm that this circuit functions properly for operating voltage down to 50 mV. The demonstration of reliable operation of relay-based digital ICs at voltages of 50 mV is a major legacy achievement of the Center for E^3S.

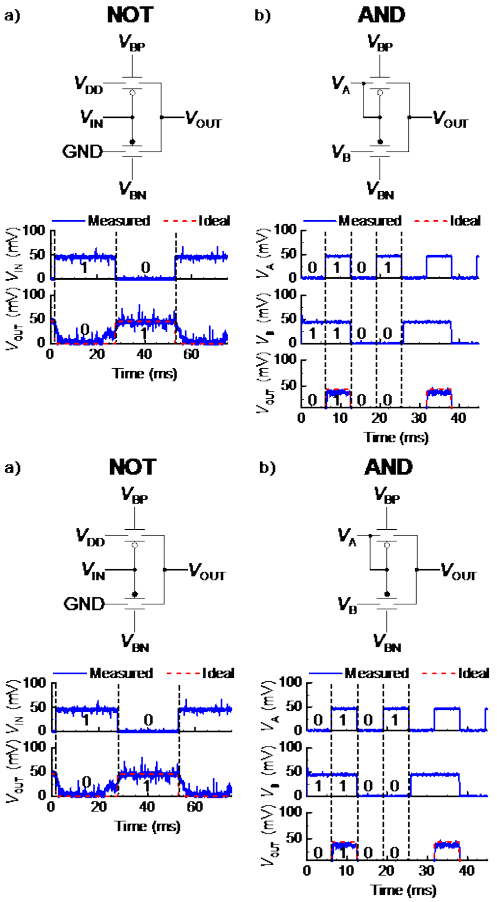


Figure 2.14. Schematic 50-mV timing diagrams and measured voltage waveforms for a NEM-relay-based a) NOT gate, b) AND gate, c) OR gate, and d) XOR gate, operating at 50 mV.

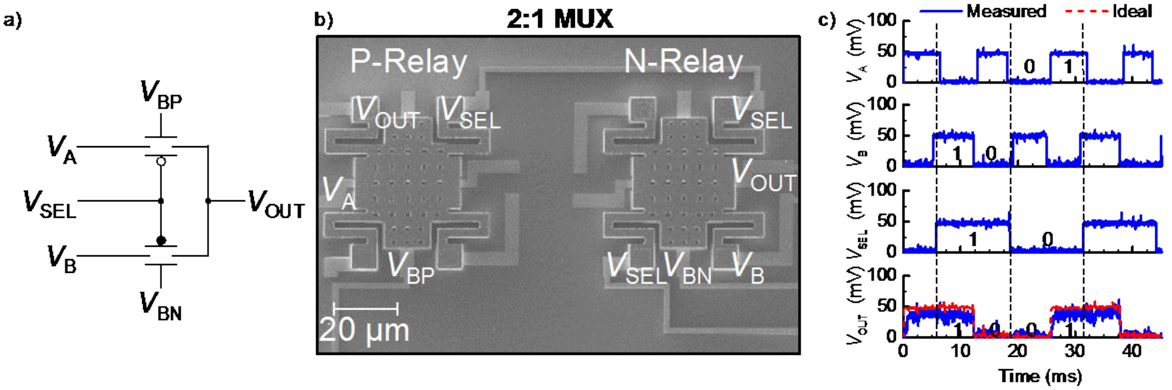


Figure 2.15. Schematic 50-mV timing diagram (a), top-view SEM image (b), and measured voltage waveforms (c) of a 2:1 multiplexer functioning at 50-mV operating voltage.

IIc. Squitch: Molecular Squeeze-Switch

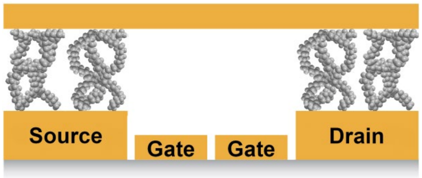


Figure 2.16. Graphic illustration of a four-terminal NEM switch employing a molecular monolayer to define and support its tunneling gap ("squitch").

The research groups of **Vladimir Bulović**, **Jeffrey Lang** and **Timothy Swager** (all *MIT*), in collaboration with the **Liu** group at *Berkeley*, have continued development of a NEM switch designed to conduct via tunneling through an electromechanically compressed gap containing "squeezable" molecules [9]. This "squeezable" switch was invented under E^3S and has also been termed a "squitch". An illustrative four-terminal squitch is shown in Figure 2.16, and is labeled as per an equivalent MOSFET. In this switch, a vertically-movable conductor is supported by a molecular monolayer that is compressed upon application of a gate-gate voltage, thereby permitting source-conductor-drain electron tunneling. The split gate is recessed to prevent gate-conductor tunneling. Note that the drain/source-conductor gap separation is only several nanometers.

In the last two funding periods, research efforts in the Squitch group focused on the development of process steps and flows for the fabrication of squitch tunneling gaps having nanoscale smoothness, planarity and dimensional precision with high yield [45]. This optimization process resulted in the successful fabrication of a four-terminal squitch device, as reported last year. This year, the group returned to focusing on fabrication and materials, with the intent of improving yield and squitch performance. Each process step was characterized to identify the most risky step in the fabrication flow. Most of this work was carried out with two-terminal squitches for convenience. Additionally, two-terminal squitches were used to investigate the mechanical behavior of the molecular films as they cyclically compress and elongate during switching, and to experimentally bound the switching time of the squitch.

The fabrication process flow is shown in Figure 2.17 for a four-terminal squitch. The process begins with a sub-nanometer-smooth handle wafer onto which a sacrificial 4-nm-thick graphene layer is placed. The sacrificial material is then patterned using a plasma etch in concert with an electron-beam-defined mask. Next, thermally-evaporated gold electrodes are deposited and patterned via lift-off using an overhung bilayer electron-beam-defined mask. Importantly, the underside of the source and drain electrodes are as smooth as the handle wafer. Furthermore, the undersides of the gate electrodes are elevated with respect to the source and drain electrodes due to the sacrificial material beneath them. This elevation will eventually become a recess. Next, the electrode structure is bonded to a receiving substrate with epoxy, and then peeled off the original substrate to reveal planar nanometer-smooth drain and source electrodes. A fluorinated molecular layer assembled on the original substrate assists the peeling step. The final step of electrode fabrication is to remove the sacrificial layer using a plasma etch, revealing gate electrodes that are slightly recessed to prevent gate tunneling. The last two steps of squitch fabrication involve the self-assembly of the molecular monolayer that occupies the squitch tunneling gap, and the placement of gold nanorods above the squitch electrodes using dielectrophoresis. At present, the molecular monolayer comprises thiolated polyethylene glycol. Note that a two-terminal squitch does not comprise gate electrodes. Therefore, the sacrificial material and its associated fabrication steps are not required, greatly simplifying squitch fabrication.

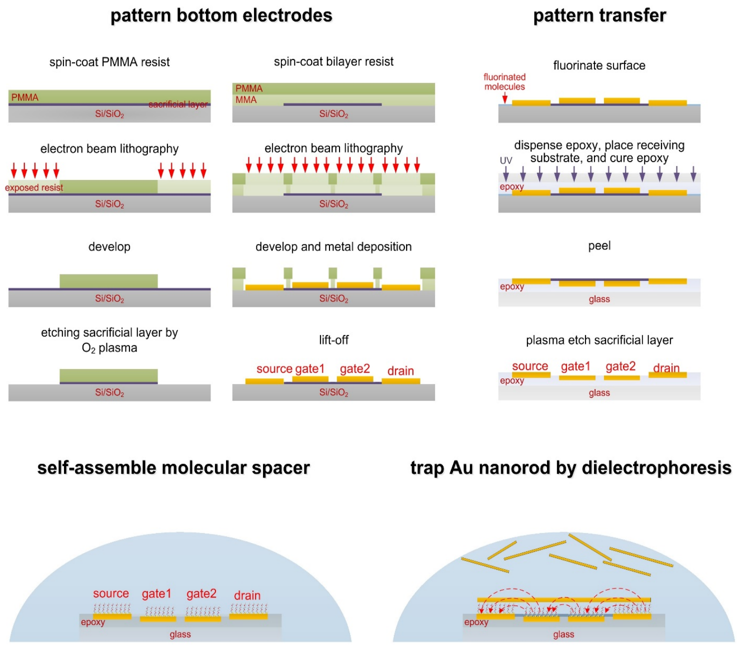


Figure 2.17. Process flow for fabrication of a four-terminal squitch device.

The yield of the critical squitch fabrication steps was characterized, and with the exception of the dielectrophoretic trapping of suspended gold nanorods, all steps exhibited nearly 100% yield. Trapping, on the other hand, was measured to have a yield less than 20% depending on the voltage amplitude and frequency of the excitation used to drive the dielectrophoresis. Detailed trapping yields are shown in the figure below. There are several reasons for the lower yield. The first reason is that gold nanorods tend to agglomerate in suspension, and this agglomeration carries over during trapping. Gold agglomerates do not function well as suspended electrodes. The second reason is that the gold nanorods are only weakly bonded to the molecular monolayer. Therefore, as the dielectropheresis solution dries, the receding edge of the solution can carry a nanorod off the electrodes. On the other hand, when trapping works, it readily yields functional squitches as illustrated in Figure 2.18.

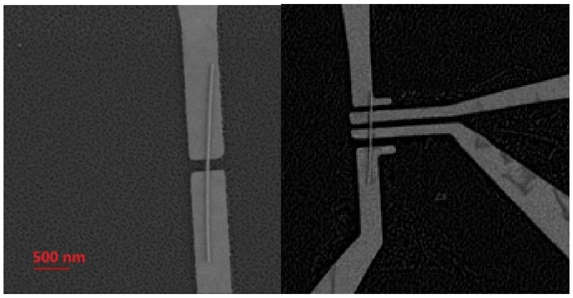


Figure 2.18. Gold nanorod dielectrophoretically trapped in a two-terminal squitch (**left**) and a four-terminal squitch (**right**).

The team also characterized the conduction process and switching delay of two-terminal squitches fabricated as described above; two-terminal squitches were chosen because they are more convenient to fabricate than four-terminal squitches. Two-terminal squitches have been measured to actuate at approximately 2 V, and exhibit a subthreshold slope of approximately 40 mV/decade over 5 decades of current. The switching delay of a two-terminal squitch is illustrated in Figure 2.19. In the experiment, a voltage source, a resistor and a squitch are connected in series. As the source voltage (black) steps, the squitch switches on, and correspondingly the voltage across the resistor (red) rises. From this measurement, the squitch switching delay is approximately 20 ns. Typical results for different devices were in the 20-40 ns

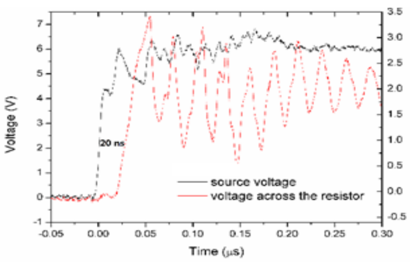


Figure 2.19. Illustration of switching delay by a squitch switching transient.

range as an upper bound. Improved experimentation will be performed in the future to determine the switching delay more accurately.

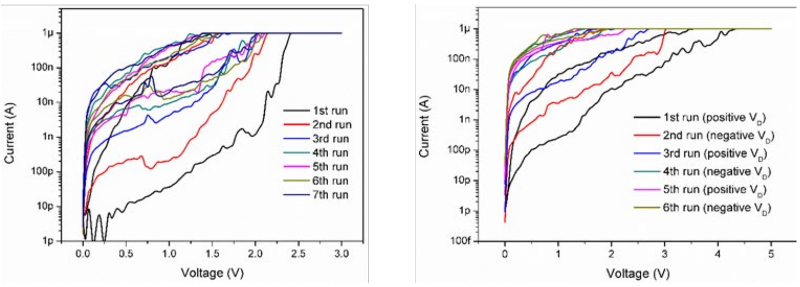


Figure 2.20. Squitch current plotted against voltage over several closing and opening cycles for two different experiments. A 1 µA current limit is imposed by the exciting power supply. Further, in the right-hand experiment, the sign of the applied voltage was toggled after each cycle.

The molecular monolayer play a critical role in squitch devices. It defines the conduction gaps, provides a scaffolding to support the movable conductor and a spring to restore its position upon removal of the gate-gate voltage, and it prevents direct metal-metal source/drain-conductor contact thereby alleviating stiction problems. To gain detailed insights into the mechanical behavior of the commonly used polyethylene glycol molecular monolayer during squitch cycling, a novel metrological experiment was conducted. This examination has revealed that the monolayer permanently deforms as the squitch gap is closed and opened. The deformation can be observed in Figure 2.20, which contains the results of two experiments. In each experiment, as the number of compression/decompression cycles progresses, the squitch current drifts upward indicating that the squitch does not fully reopen after closure. Interestingly, this behavior was not observed with earlier molecular layers formed from fluorinated alkane thiols.

IId. Stritch: 2D Chalcogenide Stretch-Switch

The Stritch project has continued to be led by **David Zubia**'s group (*UTEP*) in close collaboration with the **Liu** and **J. Wu** groups (both *Berkeley*). The "stritch" concept is a "stretchable switch" that makes use of the change in bandgap and conductivity of 2D chalcogenide semiconductor layers upon stretching [46]. In the past two periods, proof-of-concept of the stritch was established using a micro-electro-mechanical (MEM) cantilever actuator that was not specifically designed for the stritch device. Two main failures modes were identified: 1) detachment of TMD from the MEM actuator and 2) TMD rupture during high stress. To address these issues, existing MEMS comb-drive actuators were tested. However, two problems were revealed in the existing MEMS actuators after release, which prevented their use. One problem was residual stress damage and the other was finger deformation at high voltage as shown in Figure 2.21.

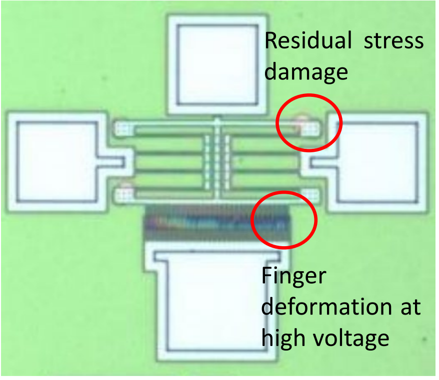


Figure 2.21. Existing MEMS comb drive actuator showing post-release residual stress damage and finger deformation at high voltage.

To overcome these problems, a new MEMS comb-drive actuator was designed by the **Zubia** group in collaboration with the **Liu** group. In this period, the new comb-drive MEMS actuators was fabricated (Figure 2.22; left) and 2D-TMDC samples were transferred onto the actuator to test their electrical and optical properties under strain. The group demonstrated a 3000-fold increase in conductivity in MoS_2 flakes stretched to a record 3% strain as shown in Figure 2.22 (center). Photoluminescence and Raman measurements corroborated the electrical data. Theoretical analysis of the stritch device implemented as an inverting circuit showed significant voltage gain derived from strain due to the deformation potential, as shown in Figure 2.22 (right). To achieve the demonstrated 3000-fold conductivity increase in MoS_2 by straining, vertical actuation was used instead of horizontal actuation as originally intended. This limited the strain to a maximum of 3%, however. To allow for optical measurements to be made simultaneously with electrical measurement, a simplified MEMS actuator – which should improve manufacturability as well as testability – was designed with the aid of 3-D simulations. This new actuator design will be fabricated and tested in period 10.

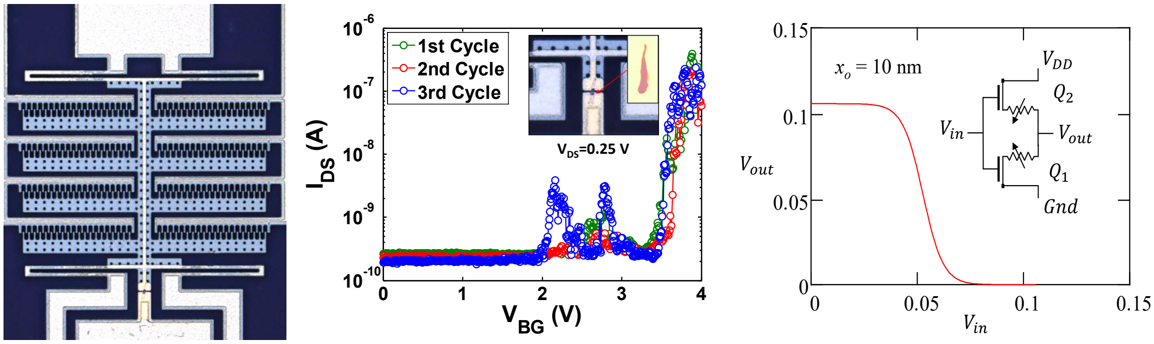


Figure 2.22. Left: SiGe MEMS actuator. **Center:** 3000X increase in conductivity in strained MoS2. **Right:** Transfer function of strich inverter shows significant gain derived from produce of deformation potential of 2D-TMDC and strain sensitivity of MEMS.

2aiii. *Theme III: Nanophotonics* *Theme Leader:* **Ming C. Wu** *(UC Berkeley)*

The goal of the nanophotonics theme is to develop highly efficient solutions for on-chip optical communication between electronic gates. In fact, E^{3}S nanophotonics researchers attempt to approach experimentally the quantum limit of photons-per-bit in a data-link: from currently used ~20,000 photons per bit to just a few hundreds of photons per bit. To meet this goal, the Center has focused on exploring new optical materials, developing new nanofabrication methods for optical components, and integrating components into energy-efficient on-chip systems. Key challenges are to miniaturize novel, ultra-efficient optical components (photoemitters and photoreceivers) to be comparable to the size of transistors, and to connect these components with waveguides at unprecedented coupling efficiencies into integrated systems. These challenges are addressed by the E^{3}S nanophotonics team in a collaborative approach by **Ming Wu** (theme leader), **Eli Yablonovitch**, **Vladimir Stojanović, Connie Chang-Hasnain** (all *Berkeley*), and **Gene Fitzgerald** and **Jeehwan Kim** (both *MIT*).

Central to the Center's nanophotonics research endeavors has been to demonstrate the enormous potential of antenna enhancement on optical components with the goal of replacing the laser—the ubiquitous light source in optical communications today [11, 26]—with light emitting diodes (LEDs). High-speed nano-LEDs are great candidates for energy-efficient, fast and small optical emitters for on-chip optical interconnects. A breakthrough result by E^{3}S researchers was the demonstration that spontaneous emission from antenna-enhanced nanoLEDs can indeed be faster and more energy efficient than the stimulated emission in lasers. Spontaneous emission enhancements of more than 300 times was achieved under optical excitation [27]. In the last period, another milestone was reached by demonstrating >200-times increase in the spontaneous emission rate under *electrical excitation*—more than doubling previously reported enhancements [47].

While E^{3}S focused initially on antenna-enhanced light emission, similar enhancement strategies are also considered at the photoreceiver end. This strategic change was done in response to important findings at the system integration level. In-depth analysis revealed that the photodetector must be sufficiently large to absorb the photons, while the high-speed pre-amplifier must be small to minimize transit time and provide sufficient gain, presenting mutually conflicting requirements [10]. As a result, the Center decided to eliminate the photo-transistor effort in the Center, which tried to combine both functions in a single device. Instead, a transition toward a systems level solution is sought. Some of the new features that will be needed to make a more sensitive photoreceiver are (1) a cavity enhanced photo-diode, (2) a very large feedback resistor on the initial trans-impedance amplifier (compensated by high-pass frequency response in the succeeding amplifier stages), and (3) multiple serial-to-parallel slicers that split the load on the parallel slow comparators, which decide whether the bit is 1 or 0.

During this funding period, implementation of an important personnel change has started at MIT. **Gene Fitzgerald** (*MIT*) will phase out of the Center by the end of the current period due his extensive commitments at a research lab in Singapore. **Jeehwan Kim** (*MIT*) will take over the semiconductor growth facility from **Fitzgerald** at MIT and he will continue the nanoLED growth project in close collaboration with the **Wu** group in the nanophotonics theme. An additional focus will be on 3D integration of nanoLEDs on silicon substrates utilizing the 2D material based layer-transfer-technique developed in the **Kim** group [48].

The following provides details of period 9 research efforts in the nanophotonics theme on:

IIIa. Antenna-Enhanced III-V nanoLEDs
IIIb. 2D-Chalcogenide nanoLEDs
IIIc. Coupling of Antenna-nanoLEDs to Optical Waveguides

IIIa. Antenna-Enhanced III-V nanoLEDs

The **Wu** and **Yablonovitch** groups at Berkeley have continued their close collaboration with the **Fitzgerald** group at MIT (and recently with the **Kim** group at MIT) with the goal to further optimize the efficiency and direct modulation rate of the III-V antenna-LED developed at E^{3}S [26, 27]. Significant achievements in the last two research periods led to the milestone demonstration of a 200-fold increase in the spontaneous emission rate of a III-V antenna enhanced nanoLED under election injection—the best spontaneous emission enhancements reported for a device under electrical injection. This breakthrough was the result of optimization of antenna design and process improvements, and of replacing the "bulk" InGaAsP active region with a quantum well InGaAs active region developed in the **Fitzgerald** group. Moreover, with assistance by the **Javey** group, the team successfully improved the device efficiency by a factor of ten through a decrease in the surface recombination velocity at the active region surface. This was achieved through the deposition of a sacrificial Al_2O_3 layer.

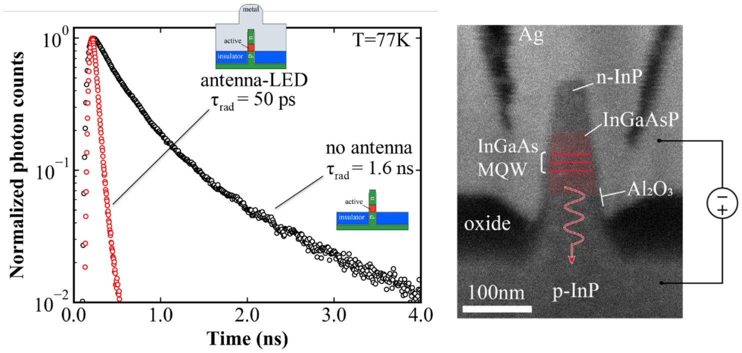


Figure 2.23. Left: Time-resolved photoluminescence measurements of an antenna-LED device and bare emitter without antenna measured at 77 K. **Right:** Cross-sectional SEM image of fabricated nanoLED.

In period 9, the **Wu** group was able to utilize this significant increase in the device efficiency to perform time-resolved photoluminescence measurements of the spontaneous emission lifetime of the III-V antenna-LED. These first-of-a-kind measurements for antenna-enhanced nanoLEDs revealed ultrafast spontaneous emission lifetimes in the 50 ps range at 77 K. Figure 2.23 compares the time-resolved photoluminescence response of an antenna-LED device and with that of a bare emitter without antenna, both measured at 77 K. A ~30-fold reduction in the spontaneous emission lifetime was observed for the device with antenna. This is the "overall" enhancement averaged over the entire spontaneous emission spectrum. Note that previously it was only possible to report the maximum enhancement.

In parallel, the Wu group teamed up with **Michael Bartl** (*Berkeley*) and started a new project to incorporate colloidal quantum dots into the antenna-LED emitter. Quantum dots have several benefits such as wavelength tunability, high efficiency, and flexibility in processing including the use of arbitrary substrates. In initial studies, the group successfully integrated colloidal CdSeS/ZnS quantum dots into a slot antenna active region. This was achieved by selective-area deposition of the quantum dots into the slot region by filling the slot with surface-functionalized oxide and using conjugation chemistry to selectively attach quantum dots to the oxide by covalent bond formation. Figure 2.24 shows a photoluminescence image and corresponding spectra demonstrating the selective-area deposition. Some undesirable light emission was observed outside of the slot region. This "off-slot" light emission will need to be reduced in follow-up studies to allow for the next

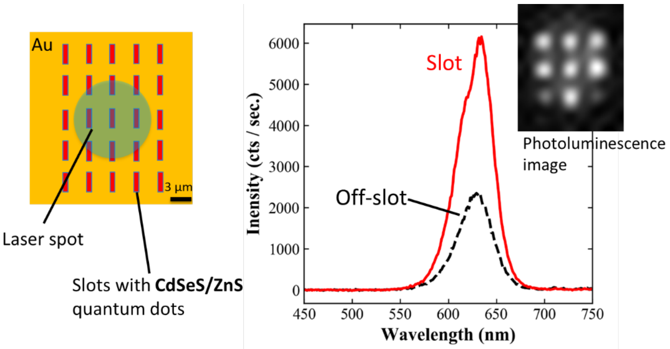


Figure 2.24. Left: Schematic of quantum dot activated slot antenna arrays. **Right:** Photoluminescence spectra and image (inset) confirming the selective-area deposition of quantum dots.

steps. In particular, measuring the spontaneous emission lifetime and determining the antenna enhancement of the spontaneous emission.

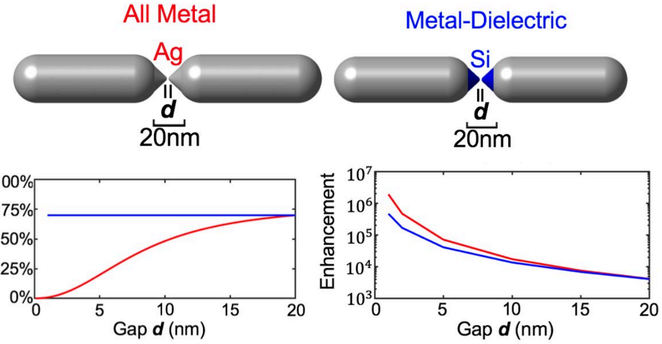


Figure 2.25. Top: Schematic structures of all-metal (left) and metal-dielectric (right) dipole antennas. **Bottom:** Efficiency and enhancement of the antennas as a function of the gap thickness *d*.

In a new research effort, the nanophotonics team started exploring the fundamental limits of antenna enhancement in this period. In general, Ohmic loss due to spreading resistance and the anomalous skin effect impairs the efficiency of optical antennas, consequently limiting the spontaneous emission rate enhancement that would otherwise be achievable [49]. In response, a metal-dielectric antenna has been developed that overcomes this problem by using dielectric tips to efficiently concentrate light near an optical emitter. Figure 2.25 depicts the structure of an all-metal dipole antenna compared to a similar metal-dielectric dipole antenna. The efficiency and enhancement of the antennas are plotted as a function of the gap thickness *d*. For feature sizes less than 10 nm, the efficiency of the metal-dielectric antenna is constant and achieves ultra-high broadband spontaneous emission enhancement relative to the all-metal antenna. Use of a similar metal-dielectric antenna could enable efficient, ultra-fast next-generation LEDs. Furthermore, the device is capable of electrical injection, thus making it a potential candidate for a next-generation optical antenna-enhanced nanoLED.

IIIb. Chalcogenide antenna-LEDs

The **Wu** group, in collaboration with the **Yablonovitch** and **Javey** groups, has made tremendous progress in the development of transition metal dichalcogenide (TMDC) monolayer antenna-enhanced LEDs. In the last several period, the team demonstrated the first optically pumped antenna enhanced spontaneous emission from a TMDC monolayer [50], light emission from TMDC monolayers by electrical charge injection [51], and bright electroluminescence at ambient conditions by pulsed electrical injection of WSe_2 monolayers [28]. In this period, the group sought to understand the underlying mechanism for this bright emission. In particular, they have investigated the physical mechanisms responsible for improved light emission with pulsed injection at ambient conditions (Figure 2.26). Results obtained so far point to ambient humidity as well as intrinsic hole trapping as the dominant mechanisms causing current decay at ambient conditions.

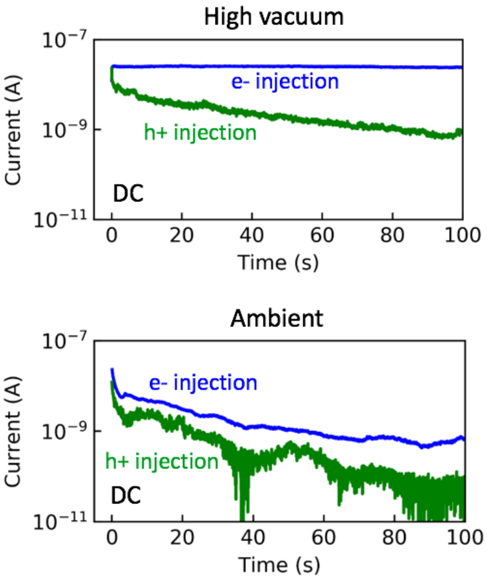


Figure 2.26. Current decay behavior of TMDC monolayers by pulsed electrical injection in vacuum and at ambient conditions.

In addition, the chalcogenide team put significant effort into optimizing the process conditions to obtain the highest electroluminescence quantum efficiencies to date (~1%), shown in Figure 2.27. In fact, this value is comparable to the photoluminescence quantum efficiency, indicating efficiency is limited primarily by material quality. The quantum efficiency values are on par with the best results in literature [29, 30]. It should be emphasized that unlike past work, which has focused on electroluminescence in high vacuum, the current E^{3}S results are obtained from devices operated at ambient conditions. The next steps of this project will aim at coupling these devices to antennas and enhance emission speed and efficiency.

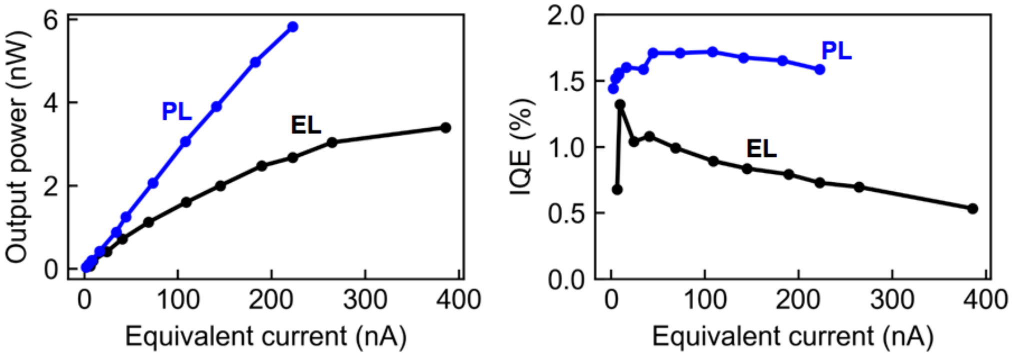


Figure 2.27. Photoluminescence and electroluminescence output power (**left**) and internal quantum efficiency (**right**) of TMDC monolayers.

IIIc. Coupling of nanoLEDs to Optical Waveguides

While the antenna-enhanced nanoLEDs developed in the Center for E^{3}S show great promise as small, efficient, and electrically injected light sources, little work has been done on coupling these devices to waveguides. However, the efficient coupling of nanoscale optical components to waveguides is of utmost importance for the development of on-chip integrated photonic links. Starting in the last funding period, the E^{3}S nanophotonics research groups of **Eli Yablonovitch, Ming Wu**, and **Connie Chang-Hasnain** addressed this challenge using electromagnetic design techniques to engineer and optimize coupling efficiencies of nanoLEDs to single mode optical waveguides. Initial efforts focused on two distinct coupling geometries: 1) Coupling design with a flat facet reflector and a parabolic reflector. Using the Lumerical 3D FDTD solver, >90 percent waveguide coupling for the parabolic reflector into a single mode InP waveguide with over a 380nm 1dB bandwidth was achieved. Waveguide coupling is defined here as the ratio of power radiated into the waveguide vs. total power radiated into the farfield.

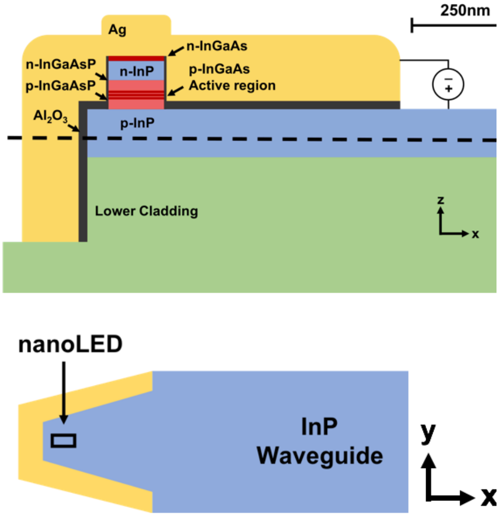


Figure 2.28. **Top:** Cross-sectional view of the antenna nanoLED coupled to an InP waveguide in the tapered coupler design. **Bottom:** Top-view of the design cross-cut along the broken line in top image.

In period 9, the group made significant progress in the coupling efficiency and overall performance by applying electromagnetic inverse design techniques. The starting structure was an antenna nanoLED coupled to an InP waveguide in the tapered coupler design (Figure 2.28). A major challenge in coupling light emitted from the antenna-enhanced nanoLED into a single mode waveguide is that the antenna's emission is directed primarily into the substrate. Figure 2.29 shows the structural evolution of the coupler design obtained through a combination of hand optimization and inverse design optimization *via* the adjoint method. The important device characteristics in the optimization process were the coupler average (spectral, spatial, and polarization averages) enhancement, F_{ave},

Name	XY Cross-Section	F_{avg}	η_{WCEQE}	$F_{avg}\times\eta_{WCEQE}$
Bulk InP		159.8	0.542* *into all space	86.7
Tapered Coupler		161.1	0.432	69.7
Inverse Design: High Speed		168.9	0.327	55.2
Inverse Design: High Power		143.5	0.608	87.2

Figure 2.29. Structural evolution and coupling parameters for different coupler designs between antenna-enhanced nanoLED and a single mode waveguide.

which is indicative of the device speed (e.g., $F_{avg} > 100$ corresponds to ~100 GHz direct modulation rate), and the total waveguide-coupled external quantum efficiency, η_{WCEQE} (which includes metal losses). Note that η_{WCEQE} of the bulk InP structure is simply the antenna efficiency in this case (metal loss), because it is allowed to radiate into all space. The right column of Figure 2.29 gives the product of enhancement and quantum efficiency. This value is important since it is indicative of the total power that is transmitted into the fundamental mode of the waveguide. The optimized structure and parameters are given at the bottom of Figure 2.29. This coupler design is capable of >95% coupling efficiency, corresponding to 60.8% total waveguide-coupled external quantum efficiency. Importantly, the overall enhancement, including polarization and spatial averaging, of the device is 143.5, which would enable >100 GHz direct modulation. Moreover, the optimized structural design of the electrically injected cavity-backed slot antenna nanoLED with >95% waveguide coupling efficiency is fully compatible with top-down fabrication methods. Efforts in the upcoming research period will be directed to applying this analysis in an experimental demonstrate of an optical link.

With this optimized waveguide-coupled antenna-enhanced nanoLED in hand, the **Wu**, **Stojanović**, and **Yablonovitch** groups teamed up to simulate a full digital-to-digital optical link with inclusion of the receiver. Reasonable values were assumed for the photodiode [12], and the CMOS receiver's extrinsic current-unity gain. The receiver model considers not only resistor thermal noise and transistor FET noise, but also the input swing sensitivity required to have an output rail-to-rail signal. All of these metrics combine to yield a topology and data-rate specific energy-per-bit (E/b) both for the receiver side and transmitter side. For each data-rate, an optimization was performed to find the minimum E/b sweeping over the number of linear amplifiers (N), the number of interleaves (M), and the FET sizing. As shown in Figure 2.30, E/b values below 1 fJ/bit can be achieved for data rates of up to 100 Gbps assuming high fT of 260 GHz within the receiver. Such high fT is achievable with 22 nm FDSOI technology. Ultimately, the nanoLED power imposes a restriction on the maximum attainable data-rate for the link. Due to a small active region it is constrained to approximately 2-3 µW of output power. The team is currently pursuing improved nanoLED design to further increase the output power.

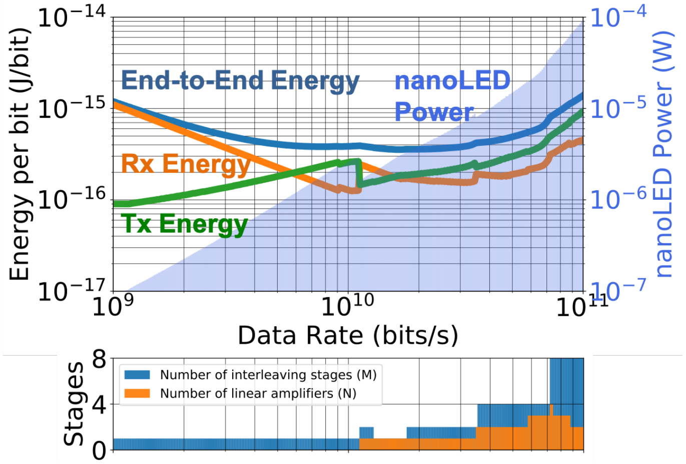


Figure 2.30. Energy-per-bit and nanoLED power as a function of data rate for a full digital-to-digital optical link with nanoLED emitter, waveguide, and receiver.

2aiv. *Theme IV: Nanomagnetics* *Theme Leader:* **Jeffrey Bokor** *(UC Berkeley)*

The nanomagnetics theme develops current-driven magnetic elements for electrical communication with switching energies at the sub-femtojoule level and ultrafast switching speeds (below 10 picoseconds). Magnetic systems are attractive low-energy switching candidates since the constituents tend to be metallic and therefore have a low voltage requirement. In addition, the non-volatility of magnets can be used to reduce the static power losses. However, magnetics-based switching will have to overcome two major hurdles to be of interest for industrial device applications: the low speed of magnetic switching and the low ON/OFF ratio of state-of-the-art magneto-resistors.

Led by theme leader **Jeffrey Bokor** (*Berkeley*), the multi-institutional nanomagnetics team at E^{3}S addresses these very challenges of magnetics-based switching. In addition to the Bokor group, the research team is comprised of the groups of **Sayeef Salahuddin** (*Berkeley*), **Vladimir Stojanović** (*Berkeley*), **Sakhrat Khizroev** (*FIU*), and **Shan Wang** (*Stanford*) who replaced **Philip Wong** (Prof. Wong left the Center and Stanford to take on a leadership position at TSMC). This team takes advantage of spin-transfer torque magnetic tunneling junctions and newly discovered ultra-sensitive current driven switches employing actuated spin-orbit torque (spin-Hall effect) to switch a magnet, which in turn changes a voltage-biased magneto-resistor, producing output current [13]. Such a component can have current in/current out gain, as well as fanout. In addition, the nanomagnetics team employs novel ultra-fast hot-electron switching methods [52-54] to counter the inherently low fundamental switching speed of conventional nanomagnetic devices. All current magnetic switching devices are limited in speed by the fundamental precessional frequency of ferromagnetic materials, which is generally in the range of 10 GHz, and device switching speeds are in the range of 1 nanosecond.

Starting in funding period 7, the **Bokor** and the **Salahuddin** groups focused on understanding the fundamental physics and underlying switching dynamics of spintronic phenomena. They demonstrated that demagnetization of ferromagnetic compounds could be achieved at picosecond time scales by hot electrons that are excited via direct heating with a short laser pulse. Subsequently, the team showed that it is possible to extend this switching phenomenon to electrical pulse excitation [14, 53]. Research in the previous funding period was aimed at realizing ultrafast switching in other magnetic materials. By exchange coupling a ferromagnetic material (Pt/Co multilayers) to GdFeCo, the Bokor group observed ultrafast optical switching of the ferromagnet [55]. They have also demonstrated ultrafast optical switching in new ferromagnetic alloys including GdCo and GdTbCo. In this period, the main goal has been to scale electrical switching to nanosized magnetic structures in order to reduce the required switching current and achieve total switching energies that are similar or lower than in current state-of-the-art logic switches.

Part of the E^{3}S nanomagnetics team (**Salahuddin** and **Wang** groups) has also started to explore new ways to reduce current needed to switch magnets using a spin orbit torque. In particular, the team found that topological effects are promising avenues to reduce current and identified several topological insulator materials as interesting spin transfer torque candidates. The **Khizroev** group in collaboration with the **Bokor** group has continued research on the fabrication and characterization of square spin-transfer torque based magnetic tunneling junction devices. In this period, nanoparticle-based devices with critical sizes as small as 2 nm were fabricated [56]. These devices have shown superior properties such as tunneling magnetic ratios (TMR) exceeding 1000% ("ON/OFF" ratio equivalent), record small switching current densities (< 1 MA/cm^2), and multilevel devices with improved energy efficiency and information processing capabilities [57].

The following provides details of period 9 research efforts in the nanoelectronics theme on:

IVa. Picosecond Magnetic Switching
IVb. Spin-Orbit Torque Switching
IVc. Magnetic Tunneling Junction Devices

IVa. Picosecond Magnetic Switching

In the last two periods, the **Bokor** group in collaboration with the **Salahuddin** group made several breakthrough discoveries in ultrafast switching of magnetic materials. Building on prior work that has shown that demagnetization in the picosecond time range can be enabled by hot electrons that are excited via direct heating with a short laser pulse [54], the E^{3}S team developed a more practical approach by injecting hot electrons into the magnet by application of a short, low-voltage electrical pulse (Figure 2.31). This approach enabled electrical ultrafast switching of ferrimagnets [14, 52, 53], ferromagnetic alloys including GdCo and GdTbCo, and ferromagnetic Pt/Co multilayers by exchange coupling to GdFeCo [55].

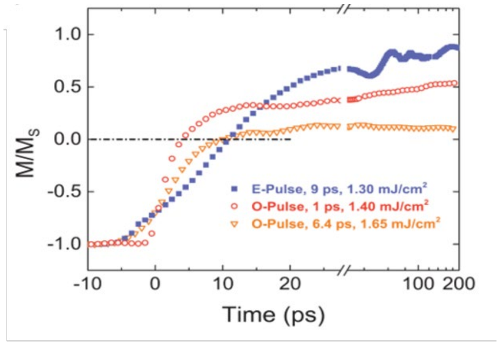


Figure 2.31. Ultrafast magnetic switching behavior of ferrimagnetic GdFeCo as a function of excitation pulse type and width.

The ultimate goal of the E^{3}S nanomagnetics team is to inject hot electrons into the magnet by application of a short, low-voltage, on-chip electrical pulse. Conventional CMOS scaling is projected to reach transistor speeds in the range of a few picoseconds, so such electrical pulses will be available on-chip. A joint collaboration was formed among the **Bokor**, **Salahuddin**, and **Wong** groups to integrate magnetic device structures on advanced CMOS chips in order to test magnetic switching and readout triggered by electrical pulses generated directly by CMOS circuits. Two challenges have to be overcome toward this goal: (1) Integration of an electrical readout into the circuit structure, and (2) reduction of both the switching energy and current to be compatible with CMOS technology.

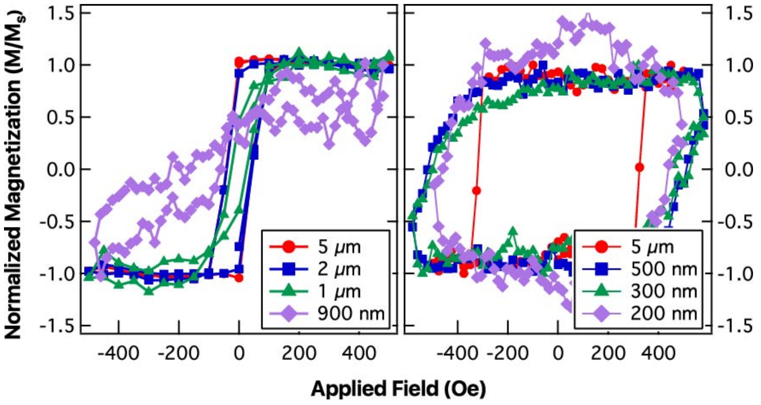


Figure 2.32. Hysteresis loops of GdFeCo (left) and GdCo (right), showing that GdFeCo dots go in-plane at smaller dimensions while GdCo dots remain out-of-plane.

In period 9, research efforts have been directed to address this very challenge by investigating how the switching energy and current scale with the size of the magnetic structure. So far, all experiments have been performed on micrometer-sized magnetic samples. However, calculations revealed that energies and currents for the electrical switching of magnets could be as low as ~3.5 fJ and ~10's of μA, respectively, for a (20 nm)^3 cell size, which would be suitable for integration with CMOS transistors. While the **Bokor** and **Salahuddin** groups succeeded in developing key fabrication processed needed to fabricate nanodots of GdFeCo down to 50 nm diameter, they also found that maintaining good magnetic properties including perpendicular anisotropy is a significant challenge. Smaller dots tend to revert to in-plane magnetic anisotropy, which is not suitable for highly scaled magnetic devices (Figure 2.32 left). However, the group recently discovered that good perpendicular anisotropy could be maintained with GdCo and GdTbCo alloys (Figure 2.32 right). Most importantly, these materials also show ultrafast switching behavior. For the GdCo alloys, ultrafast all-optical switching behavior was observed in nanoscale dots fabricated in arrays down to 200 nm diameter, which was the limit to reliably detect the magnetic state of the dots optically (Figure 2.33).

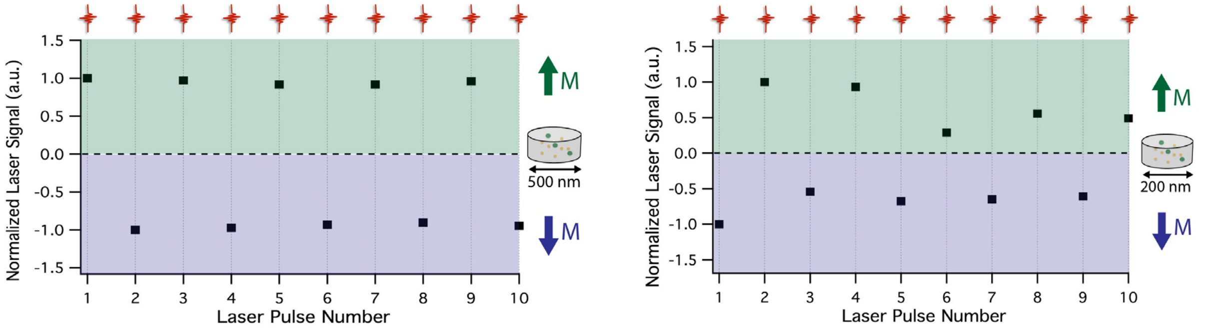


Figure 2.33. Single-shot all-optical switching of magnetic nanodots 500 nm (left) and 200 nm (right) in diameter. Note that the 200 nm diameter dots displayed much lower signal-to-noise ratios, indicating the limit of detection.

Currently, the team is working on the design and fabrication of suitable microwave circuits to test electrical switching of individual dots. The microwave circuits will deliver the required short electrical pulses to the device, and detect the magnetic state of individual dots. Good progress has already been made in this effort, and a Hall-cross device geometry capable of measuring the magnetization in GdCo nanodots down to 50 nm diameter has been successfully fabricated and tested. Simulation studies of pulse propagation on microwave striplines have guided the design for the integration of this Hall bar structure into a microwave stripline that will generate the picosecond electrical pulse and deliver it to the Hall bar. Fabrication of these structures is currently in progress (Figure 2.34). It should be emphasized that this truly collaborative project would not have been possible without the Center for E^{3}S since the joint resources to grow the materials and make the ultrafast measurements would not have been available.

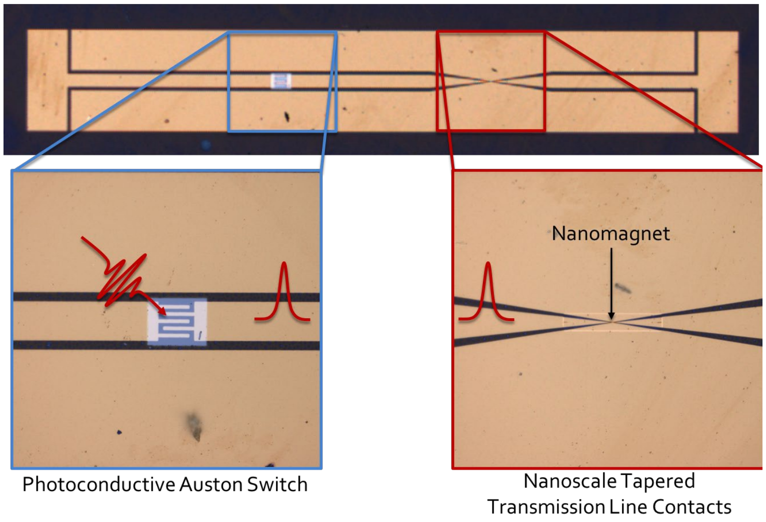


Figure 2.34. Fabricated transmission line structures with nano-tapered Hall crossbar contacting the nanoscale magnetic dot at the center.

IVb. Spin-Orbit Torque Switching

The main focus of the **Salahuddin** group is to devise ways to reduce current needed to switch magnets using a spin-orbit torque. In period 9, the group started a new direction in this quest by investigating spin transfer torque in topological insulator materials. Harmonic measurements of the longitudinal and transverse voltages in Bi-Sb/Co bilayers were investigated (Figure 2.35). In the Bi-Sb/Co bilayer sample a large second harmonic voltage signal due to the ordinary Nernst effect was observed. When a magnetic field is rotated in the film plane, the ordinary Nernst effect shows the same angular dependence in the transverse voltage as the damping-like spin-orbit torque and in the longitudinal voltage as the unidirectional spin-Hall magneto-resistance, respectively. Therefore, the ordinary Nernst effect was identified as a source of observed effects in spin-orbit torque experiments, leading to an overestimation of the spin-Hall angle in topological insulators or semimetals.

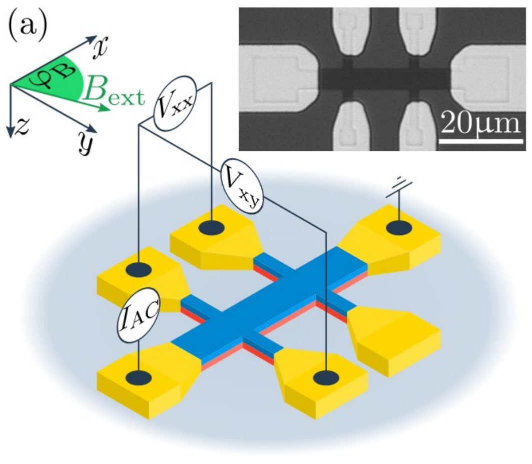


Figure 2.35. (a) Schematic set up and SEM image (inset) for harmonic measurement of spin-orbit torque.

Figure 2.36 shows the longitudinal and transverse second Harmonic voltage signals as a function of magnetic field for three different samples. In the reference Pt/Py sample, the transverse second Harmonic signal decreases with increasing external magnetic field. This is expected because large magnetic fields suppress the quasi-static magnetization oscillations induced by spin-orbit torque. On the other hand, for the samples with topological insulator Bi-Sb/Co, the transverse voltage shows a linear increase with magnetic field increase. Importantly, this behavior is very similar to another sample containing B-Sb/Al. Note that, in this latter sample there are no magnetic components and hence no reason to see any spin transfer torque. Therefore, the increasing trend is clearly a result of heating of the sample. We have done further measurement of the transverse second harmonic measurement as a function of the angle of the magnetic field. The observed behavior is consistent with the ordinary Nernst effect.

As discussed above in more detail, **Shan Wang** replaced **Philip Wong** this summer as E^{3}S senior investigator at *Stanford*. Due to this change, progress on some joint projects, such as designing circuit and system level experiments aimed at finding optimum ways of exploiting ultrafast magnetic switching for practical applications slowed in this period. On the other hand, the **Wang** group brings new expertise in the area of spin–orbit torque switching into the Center, and will work closely with the **Salahuddin** group on using topological effects for energy-efficient computing and spin-orbit torque switching. In addition, the **Wang** group is currently investigating a new two-terminal spin-orbit torque MRAM cell based on a CoFeB/MgO magnetic tunnel junction pillar on an ultrathin Ta underlayer. In this device, in-plane and out-of-plane currents are simultaneously generated when a voltage is applied.

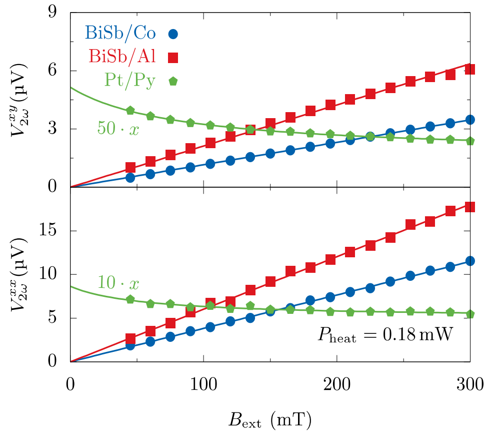


Figure 2.36. Magnetic field dependence of the second harmonic voltage in Bi-Sb/Co, Bi-Sb/Al, and Pt/Py (enhanced for visual clarity).

IVc. Magnetic Tunneling Junction Devices

The **Khizroev** group has continued its quest to answer one of the most important open question of the spin-transfer torque (STT) phenomenon: What is the dependence of the STT switching current density on the device size due to the both surface/volume and quantum-mechanical effects in the nanometer size range. This work is based on *ab initio* calculations, which have predicted that for device sizes below 5 nm, the surface-to-volume contribution to the spin effect is drastically different from that in the traditional size effect above 10 nm. In addition, calculations predict that ultra-high magnetoresistance (MR) values should be obtained in this size range. Since MR ratio is equivalent to the "ON/OFF" ratio in CMOS technology, achieving high MR values is critically important for spintronics to be competitive with CMOS. Current values for the MR ratio are around 100 percent—orders of magnitude smaller than CMOS “ON/OFF” ratios. In the last two funding periods, the **Khizroev** group developed STT magnetic tunneling junctions (MTJs) made of ferrimagnetic CoFe2O4 nanoparticles sandwiched between magnetic layers of traditional high-anisotropy CoFeB compositions [58]. The measured I-V behavior confirmed the single-electron behavior of such junctions.

In this period, the **Khizroev** group, in collaboration with the **Bokor** group, have built first batches of nanoparticle-based STT-MTJ devices with critical sizes as small as 2 nm, which are obviously driven by quantum physics. The group has shown superior properties such as extremely high equivalent “ON/OFF” ratios with tunneling MR values exceeding 1000%, and record low switching current densities (< 1 MA/cm^2). They then used this nanoparticle STT-MTJ concept combined with electron-beam lithography nanofabrication to write information not into two but into three layers (Figure 2.37). To read the resulting multilevel signal information back, we used the tunneling MR effect. The written/read back information had a ternary (not binary) signal format [31]. This collaborative, inter-institutional work demonstrated the feasibility of using the STT effect to write multilevel information into a multilayer MTJ stack via a spin-polarized current and read back the multilevel information. These results will pave the way for a new computing paradigm, which uses spin polarized currents to write and read back multilevel signal information.

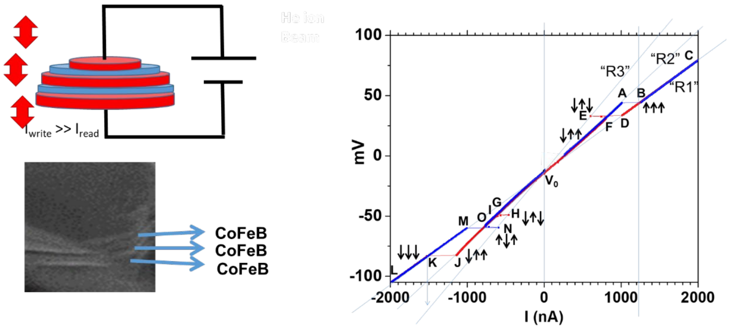


Figure 2.37. Left top: Equivalent circuit showing a three-layer STT-MTJ device for ternary signal processing. **Left bottom:** TEM image of a nanoparticle-based STT-MTJ device with two magnetic interfaces. **Right:** *I-V* curve showing ternary signals from the three-layer STT-MTJ. The information was read back through the TMR effect.

2av. System Integration *Leader:* ***Vladimir Stojanović*** *(UC Berkeley)*

From the very start of the Center for E^3S, System Integration was regarded as an important and integral part of its research endeavors. System Integration at E^3S overarches the four research themes (nanoelectronics, nanomechanics, nanophotonics and nanomagnatics) as an integral "control organ" and checks that the component research outcomes and new scientific device concepts of the Center will actually lead to new energy-efficient system architectures, enabling future ultra-low power information technologies.

In addition, to this "control organ" function, in the last period, under the leadership of **Vladimir Stojanović** (*Berkeley*), System Integration has started a new direction by setting up a deep-learning training environment based on a tensor flow approach. This approach should enable evaluation of various hardware-related architectural tactics (network pruning, reduced resolution, *etc*.) and system-level evaluation of E^3S-relevant computing architectures (including NEM-relay ICs and spin-Hall memory devices integrated with a CMOS latch). The framework provides a means to gain insight for creating architecture-friendly network structures. Large fully-connected layers have millions of coefficients, presenting both storage and computational challenges, especially for embedded/mobile devices. While these layers can be pruned to eliminate small coefficients, it results in irregular sparse structures, which scale poorly in terms of performance due to irregular memory access. In fact, in the last period, the System Integration team showed that pruned network layers could be obtained with high relative accuracy by starting from regular computational templates by pseudo-randomizing the layer template matrix with permutations, and allowing the coefficients to only grow in these permuted locations during the training. This provided enough degrees of freedom for the network to converge with good accuracy, yet provided an easy way to map the resulting layer matrix to a computationally-friendly structure, especially for in-memory computing architectures that favor locality.

In period 9, the **Stojanović** group has developed a flexible reference architecture for artificial intelligence (AI) workloads tailored to the present and future AI algorithms. This reference architecture was designed to lower the energy per task by minimizing the data movement, enabling localized computation and sets the stage for further innovation through E^3S device and process research. To establish a clear benchmark to emerging E^3S technologies, a full accelerator instance was designed and implemented in an advanced CMOS node (16 nm). The reference architecture is designed as a parameterized generator in a higher-level hardware description language (CHISEL), which is a scala-based domain-specific language that allows powerful design parameterization. The generator architecture stores a full set of network weights on-chip through a combination of pruning and dense memory allocation, and features in-memory computation realized through reconfigurable interconnect and training-based scheduling. The generator is implemented as a combination of the accelerator module and RISC-V CPU (RISC-V is an open and free to use instruction set architecture, ISA), for flexibility in execution. It achieves 50 Tops/W (20 Top/s at 0.4 W), which represents a 50 to 100-fold improvement over the latest inference engines (TPU3, PX Xavier, Stanford EIE). The layout of a chip design instance is illustrated in Figure 2.41.

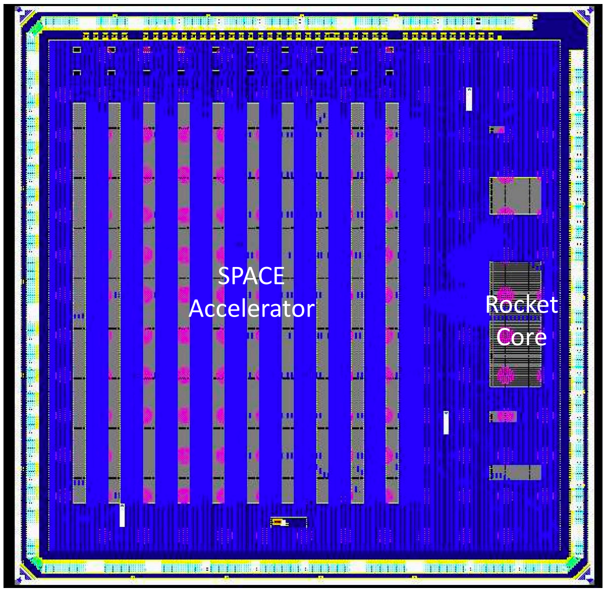


Figure 2.41. Chip design instance (2.5 mm x 2.5 mm) featuring the inference accelerator and RISC-V Rocket Core.

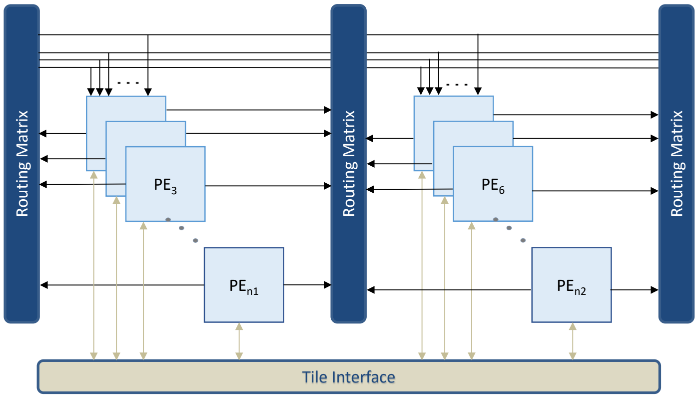


Figure 2.42. Architecture of the inference deep neural network generator.

The architecture of the accelerator is illustrated in Figure 2.42. The routing matrices allow for reconfiguration of the neural network layer to form dense localized block-level operation and coefficient weight/result memory accesses. The routing blocks further perform randomization of the dense blocks to recreate the typical fully connected layer sparsity. Figure 2.43 shows the micro-architecture details of the routing matrix and the processing element. The routing matrix is implemented in part with multiplexers that take the signals from each processing element (PE), and in part through pre-programmed read schedule from PE output SRAM blocks. This read schedule is derived during the network training, assuring there are no read conflicts between follow-on PEs. The generator allows to extract the power and area metrics for a variety of design instances, exploring the architecture trade-offs and understanding the role of each sub-block component and the opportunity for improvements through the use of advanced device technologies pursued in E^{3}S (for example the NEM relay-based non-volatile memories and reconfigurable interconnects).

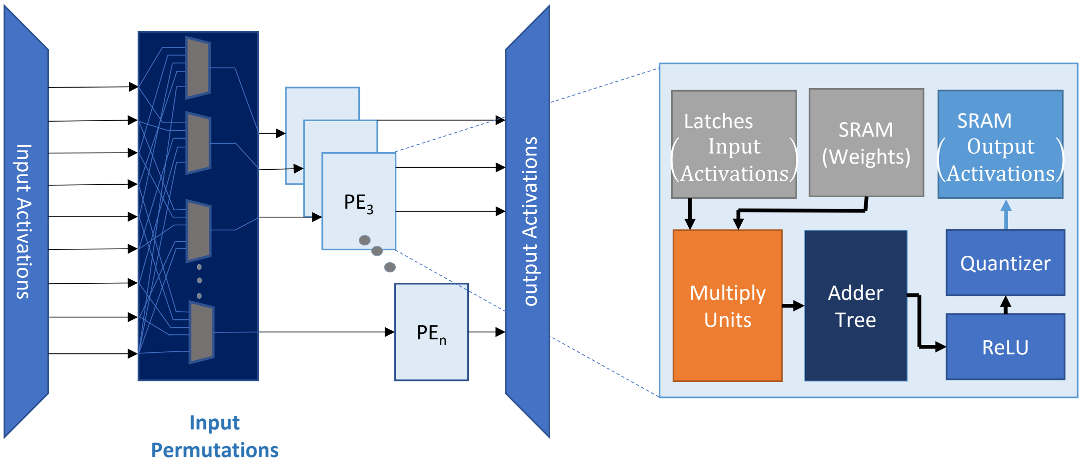


Figure 2.43. Generator micro-architecture illustrating the routing matrix and details of the processing elements.

2b. Table 2.3. Performance Against Metrics

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Research	Multi-PI projects	P2: 30% P5: 75% P6: 50% P7: 60% P8-P10: 70%	44%	67% (14)	55% (12)	64% (14)	76% (13)	65% (11)	79% (15)	89% (16)
	Multi-Institutional projects	P2: 10% P5: 30% P6: 15% P7: 20% P8-P10: 25%	4%	10% (2)	9% (2)	23% (5)	29% (5)	29% (5)	32% (6)	72% (13)
	Publications with authors from multiple institutions	P3: 12 P4: 3 P5-10: 5	0	0	1	1	3	5	2	6
	New joint research funding awards	P6: 1 P7: 0 P8-P10: 1	(new for P6-10)				0	3	1	1

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

The Center for E^{3}S continues to be a highly collaborative environment for faculty, postdocs and student researchers. This collaborative spirit is also exemplified by the high number of both multi-PI and multi-institutional projects—both exceeding the target numbers set in the Center's Strategic Plan. This highly collaborative environment has also translated into co-authorship in journal publications and conference proceedings. So far, the Center published 39 articles (including six submitted) in this reporting period, 41 percent of these articles have two or more faculty co-authors, and six of these articles are inter-institutional publications. In this period, for the first time, we will surpass the target number of joint multi-institutional journal publications. We attribute this positive development in part to steps taken by the Center leadership in recent years. In particular, the formation of a new postdoctoral research program, the Center for E^{3}S Inter-Institutional Postdoc program, and an increase in available E^{3}S Rotation program positions. The latter is a vehicle to enable current E^{3}S students and postdocs to spend mid-term (8-12 weeks) research stays at an E^{3}S partner institution other than their home institution.

2c. Research in Period 10

Research activities in period 10 will continue to be guided by the Center for E^{3}S Strategic Research Plan, and no major changes in the research directions of the four themes and system integration are planned in the next period. Except for the planned departure of **Gene Fitzgerald** (*MIT*) and the addition of his replacement, **Jeehwan Kim** (*MIT*), no further senior investigator/faculty changes are planned in period 10.

Table 2.5. Faculty Participation by Theme in Period 10

Institution	Faculty	Theme I	Theme II	Theme III	Theme IV
UC Berkeley	Bokor				x*
	Chang-Hasnain			x	
	Fischer	x			
	Javey	x		x	
	King Liu		x*		
	Louie	x			
	Salahuddin				x
	Stojanovic	x	x	x	x
	J. Wu		x		
	M. Wu			x*	
	Yablonovitch	x*		x	
MIT	Bulovic		x		
	del Alamo	x			
	Kim			x	
	Kong	x			
	Lang		x		
	Swager		x		
Stanford	Wang				x
UTEP	Zubia		x		
FIU	Khizroev				x

Legend: x* denotes theme leader

2ci. Theme I : Nanoelectronics *Theme Leader:* **Eli Yablonovitch** *(UC Berkeley)*

The nanoelectronics team consisting of the research groups of **Eli Yablonovitch**, **Steven Louie**, **Felix Fischer**, **Ali Javey** (all *Berkeley*), **Jesus del Alamo** and **Jing Kong** (all *MIT*) will continue research efforts on the development of ultralow-energy tunnel switches from 1) traditional III-V semiconductors, 2) two-dimensional transition metal dichalcogenide semiconductors, and 3) graphene nanoribbon based semiconductors. A more detailed description of period 10 nanoelectronics research plans is given below.

- *III-V Nanowire TFETs:* In the current period, the **del Alamo** group succeeded in fabricating working InGaAs vertical nanowire (VNW) MOSFETs with record low nanowire diameter of 7 nm, the target diameter for a future VNW III-V CMOS technology and a regime in which prominent single-channel electron transport is to be expected [17]. In period 10, the **del Alamo** group will continue to investigate the VNW geometry to achieve III-V transistors with steep subthreshold characteristics for both MOSFET and TFET structures. With the recent progress, it is anticipated that this project will achieve clear and clean single-channel electron transport in sub-10 nm transistors and unique insights in the sub-band structure of such an electronic system. Analysis of such behavior will be done in collaboration with the **Yablonovitch** group, including detailed temperature-dependent TFET and MOSFET characterization and noise studies. Expected major milestones are (1) the demonstration of a new mushroom-type top contact for InGaAs VNWs using selective digital etch, and (2) the *in-situ* sidewall etch and deposition of the MOS gate stack using a combination of thermal atomic-layer etching (TALE) and atomic layer deposition (ALD).

  The **del Alamo** group will also continue the collaboration with IMEC in pursuit of type-II broken-gap InAs/GaSb VNW Tunnel FETs. Last year, they developed sub-20 nm InAs/GaSb etching capabilities and delivered arrays of vertical nanowires to IMEC for device fabrication. The heterostructures are grown at IMEC, nanowire etching is performed at MIT and the rest of the process was performed at IMEC. A manuscript about these achievements will be published shortly. In the next period, it is planned to perform the entire device fabrication at MIT. Towards this goal, the group will examine TALE+ALD of the antimonide system in collaboration with University of Colorado. The **del Alamo** group is at a very productive point in this research program. Recent advances have enabled transistor structures never achieved before, and unprecedented insights in the physics and operation of ultra-scaled transistors will become possible.

- *Chalcogenide TFETs:* In the current period, the **Kong** group has successfully used MOCVD to grow monolayer MoS_2 onto a Si/SiO_2 substrate with a measured field effect mobility of ~45 cm^2/Vsec. The goal for period 10 remains to achieve high quality transition metal dichalcogenide (TMD) materials suitable for tunnel FETs, with minimal bandgap defect state density. For this, the **Kong** group, in collaboration with the Javey group, plans to synthesis large single-crystal domain TMD materials as an alternative way to decrease defect density. Since material quality is not only dependent on the synthesis process, but also the transfer and substrate/encapsulation, the team plans to develop better transfer methods (dry, vacuum transfer) and use of high quality hBN substrate/encapsulation. Mobility will be used as a measure to evaluate the quality of the materials. In addition, in collaboration with **Eli Yablonovitch**, the **Kong** group will also explore alternative 2D and 1D materials and structures for narrow-band metallic leads to implement steep switching.

  A major goal of the **Javey** group has been to visualize exciton transport in gated monolayer MoS_2. Photogenerated carriers in monolayer MoS_2 form excitons or trions depending on the concentration of background carriers, which is electrostatically controllable. From recent experiments, the group found that when the monolayer has only neutral excitons, the quantum yield is ~100%, indicating that excitons radiatively recombine despite the presence of defects. However, when the monolayer is full of trions, the quantum yield is < 0.1%, indicating a high trion non-radiative recombination rate. Therefore, excitons and trions should have different diffusion properties and interactions with disorder. The **Javey** group will team up with the **Bulović** group at *MIT* to measure the spatial, temporal and spectral character of the photoluminescence emission under different gate voltages and illumination conditions. With these data in hand, the team expects to gain a comprehensive understanding of the diffusion of different quasi-particles in these monolayers. This will have wide implications in the design of TMDC optoelectronic and electronic devices.

  In addition, the **Javey** group will explore new materials for energy filtering in TFETs. A large bandgap insulator with a defined defect level placed between the source and channel can act as an energy filter and selectively inject carriers with specific energy. Therefore, with correct band alignment, both the ON current and subthreshold swing of TFETs should improve. One such choice for 2D van-der-Waals tunnel FETs could be few-layer hBN with mono-nitrogen vacancy, where the mid-bandgap level created near the Fermi level conducts current. MoO_x also has a large bandgap with a defect level inside the forbidden gap. This project will enable to explore and categorize different wide bandgap materials on the basis of their performance in energy filtering in TFET.

- *Graphene Nanoribbon TFETs:* The **Fischer** group (guided by theoretical input of the **Louie** and **Yablonovitch** groups, and device fabrication by the Bokor group) will continue to explore and expand the rational bottom-up synthesis strategy for graphene nanoribbon (GNR) tunnel junction devices. The group recently demonstrated the ability to covalently fuse GNR segments exhibiting different topological phases into atomically defined heterostructures that feature symmetry-protected localized interface state. Theoretical calculations by the **Louie** group have demonstrated that in the case of in certain cases the topological interface states give rise to a narrow band at the Fermi energy that imparts metallic or semi metallic character to the GNR. The **Fischer** group will perform the synthesis of molecular precursors, the surface assisted assembly of topological GNRs, and the electrical characterization using scanning probe spectroscopy. In collaboration with the **Bokor** group, wet and dry transfer processes of GNRs onto insulating substrates will be developed. This will enable measurement of the conductance of metallic GNRs in a device setting.

In the past period, the **Louie** group has extended the study on topological phases in GNRs from armchair GNRs to other types of GNRs, such as cove-edged and chevron GNRs, which have been synthesized at atomic precision in the **Fischer** group. The group also demonstrated that by using the concept of topological band engineering, metallic GNRs with narrow bandwidth could be designed. In period 10, the **Louie** group plans to find several candidates of GNR structures with metallic narrow bands by first-principles calculations. The group will then team up with the **Yablonovitch** group on estimating the exact bandwidth needed for non-Lorentzian fast-decaying lineshapes. The next step is to estimate the magnitude of Coulomb repulsion of electrons on the relatively localized orbitals in the narrow band metallic GNRs. This is to prevent the designed structure from forming a Mott insulator, which is no longer metallic.

The team further plans to calculate the lineshape of the single energy level in the quantum dot coupled to the metallic GNR leads with narrow bands by tight-binding or first-principles calculations. By using the structure of the quantum dot and metallic leads with narrow bands, they will design the double-quantum-well transistor and calculate the transport properties by using first-principles calculations. In addition, the Green's function will be calculated in the maximal localized Wannier function basis, and the method implemented in the Wannier90 code will be used to calculate the transmission probabilities of conducting electron with different energies. By first-principles calculations, they will also estimate the possible ON/OFF ratio that can be achieved by this double-quantum-well transistor architecture with applying gate voltages. The transport properties of gated transistors will be calculated to investigate the possibility of breaking the 60 meV/decade swing voltage limit.

2cii. Theme II: Nanomechanics — *Theme Leader:* **Tsu-Jae King Liu** *(UC Berkeley)*

The nanomagnetics team consisting of the research groups of **Tsu-Jae King Liu**, **Junqiao Wu**, **Vladimir Stojanović** (all *Berkeley*), **Vladimir Bulović**, **Jeffrey Lang**, **Timothy Swager** (all *MIT*) and **David Zubia** (*UTEP*) will continue their efforts toward the theme's goal of demonstrating reliable nano-electromechanical (NEM) switch (or relay) operation below 10 mV using different approaches, including 1) coated body-biased NEM relays, squeezable molecular switches ("squitches"), and stretchable monolayer switches ("stritches"). A more detailed description of period 10 nanomechanics research plans is given below.

- *Low-Voltage Relay Design and Integrated Circuit Operation:* With the recent significant improvements in the **Liu** and **Wu** groups in anti-stiction coatings and relay design to minimize the hysteresis voltage of NEM-based switches, period 10 efforts will focus on the ultimate goal of this project: Demonstration of reliable room-temperature operation of relay-based digital integrated circuits at 10 mV. This would be a major E^3S legacy achievement as no other research group in the world is aiming to demonstrate such low voltage operation of digital integrated circuits at room temperature. Key scientific questions that will need to be answered along the way include "What is the fundamental lower limit of operating voltage for mechanical computing?" and "What are key properties of the optimal contact material for milli-Volt mechanical computing?" Further refinements in relay design and materials, including anti-stiction coatings, are expected to enable the achievement of the team's ultimate goal. Furthermore, systematic studies of the temperature dependence and stability of relay operating characteristics will be conducted to elucidate any reliability challenges.

  The **Liu** group will further optimize the two-contact-dimple design ("2C" design) developed in the current funding period. In detail, the relay fabrication process flow will be modified to incorporate a floating electrode (comprising a thin layer of tungsten) within the insulating dielectric (Al_2O_3) of a body-biased relay structure. Initial experimental results are expected early in period 10, to demonstrate that the pull-in voltage of a floating-gate relay can be adjusted in a controllable and permanent manner by applying a "programming" voltage pulse. The **Wu** group will continue to explore optimization of the anti-stiction coating. In particular, they will explore self-assembled molecules with different head groups to further reduce adhesion in NEM relays. The head group will be selected such that it provides a better anchoring to the relay's tungsten surface and provide higher surface-coverage. The group will also investigate 2D materials to reduce surface adhesion in NEM relays. The absence of surface dangling bonds in such materials, along with their atomic thickness and mechanical strength, promises very effective anti-stiction coatings for NEM relays.

These advances will be implemented by the **Liu** and **Stojanović** groups in their efforts to develop ultralow-voltage relay-based integrated circuits. Following the milestone achievement in this current funding period of reliable room-temperature operation of a variety of relay integrated circuits at a voltage of 50 mV, the goal for period 10 has been set to demonstrate successful operation at 10 mV. Furthermore, the team will work on demonstrating programmable relays for embedded zero-leakage memory and identifying approaches for improving relay contact resistance stability. Lastly, together with E^{3}S System Integration, a collaboration with industry partners will be established for research and development of reconfigurable interconnect technology, i.e. NEM switches implemented using standard back-end-of-line (BEOL) metal wiring layers in a conventional CMOS process.

- *Squitch Project:* The **Squitch** team (the **Bulović**, **Lang** and **Swager** groups at *MIT*), in collaboration with the **Liu** group at *Berkeley*, identified four high-level research goals for period 10. The first goal is to address the remaining fabrication challenge for two- and four-terminal squitches. That challenge is to place the upper electrode above the source and drain electrodes with high yield. The second goal is to develop molecular monolayers that enable low-voltage switching over many cycles. The third goal is to build digital circuits from many squitches. Initially wire bonding will be used to connect squitches, followed by a transition to back-side interconnects as squitch fabrication approaches 100% yield. The first circuit will be a ring oscillator. The fourth goal is to measure the dynamic performance, and explore the dynamic limits, of squitch switching. Here, the ring oscillator is enabling.

  The majority of the goals listed above have been set as a consequence of accomplishments in the recent funding period. The focus on the fabrication step, which places an upper electrode above the source and drain electrodes arises from having quantified it as exhibiting the lowest yield of all individual fabrication steps. The efforts on new molecular monolayers arises from observing the mechanical property degradation of the squitch molecular monolayers, and from the need to reduce the switching delay and lower the switching voltage measured for two-terminal squitches. Finally, the goal to develop digital circuits arises from the charter of the Center for E^{3}S and will be a major research legacy.

  Achieving the goals outlined above will necessarily lead to investigation of several key scientific questions. Most importantly, the dynamics of nanoelectromechanical systems and the mechanical behavior of molecular monolayers have barely been studied. Understanding both is key to the development of squitches that meet the objectives of E^{3}S. Four important forces balance in the squitch: inertial (which limits speed), van der Waals, molecular spring, and electrostatic. To achieve low-voltage, and hence low-energy switching, the restoring molecular spring force must minimally over-balance the attractive van der Waals force leaving the electrostatic force to drive inertially-limited switching. This is challenging because the van der Waals force is non-linear, and its balance requires a short spring by normal thin film standards. The forces have also not been collectively represented in experimentally verified models, nor have such models been used for experimentally verified system design. Further, the requisite molecular thin films are themselves novel and unstudied, and must be custom engineered. Additionally, the **Squitch** team will explore improving the device by engineering electrically active thin films from soft, non-hydrophoric materials with structures that lower their tunneling barrier as they are bent, or electrically stressed, during actuation.

- *Stritch Project*: The inter-institutional **Stritch** team with project leader **David Zubia** (*UTEP*), the *Berkeley* research groups of **Liu**, **Javey**, and **Wu**, and the **Kong** group at *MIT* will continue to develop MEMS switches based on stretching 2D materials, in particular, transition metal dichalcogenides (TMDCs). The highly inter-institutional team will study the electrical and optical properties of TMDCs strained above 3% tensile strain using a new MEMS actuator design. In the current period, the group achieved 3000-fold conductivity increase in MoS_2 by straining it to 3% using a comb-drive MEMS actuator. However, a problem encountered with the design is that vertical actuation was achieved instead of horizontal as intended. This limited the strain to a maximum of 3%. Another problem with the design is that obtaining optical measurements simultaneously with electrical measurement is prohibitively difficult due to the layout of the contact pads on the chip. In response to this, the group has designed and simulated a simplified design. In period 10, the goal will be to optimize the new MEMS design, fabricate the device, and explore new 2D materials.

2ciii. *Theme III: Nanophotonics* *Theme Leader:* **Ming C. Wu** *(UC Berkeley)*

The nanophotonics team consisting of the research groups of **Ming Wu**, **Eli Yablonovitch**, **Constance Chang-Hasnain** (all *Berkeley*) and **Jeehwan Kim** (*MIT*) will continue research toward on-chip few-photon optical communication between electronic switches at unprecedented efficiency levels of a few hundreds of photons per bit using to concept of antenna-enhanced nanoLEDs from novel III-V heterostructures and chalcogenide materials, as well as optimized waveguide coupling. A more detailed description of period 10 nanophotonics research plans is given below.

- *Antenna-Enhanced III-V and Chalcogenide nanoLEDs:* The antenna-enhanced nanoLED project, led by the **Wu** group, and in collaboration with the **Yablonovitch**, **Kim**, and **Javey** groups, aims to further improve the performance of electrically injected nanoLEDs by building on current successes. The two major efforts for III-V devices will be (1) demonstration of high-speed and efficient operation of antenna-LEDs at room temperature, and (2) demonstration of time-resolved measurements of antenna-LED speed under electrical bias. The first effort will require further optimization of the design and fabrication of the antenna-LED. The **Wu** group has already begun pursuing p-type doping of the active region and device scaling as a means to increase the speed and efficiency. These efforts will be continued. In parallel, the team is devising an experiment to directly measure the speed of the antenna-LED under electrical bias. Previously, they used a “DC” measurement to infer the speed under electrical bias. In period 10, the goal is to perform a true high-speed measurement under electrical-bias. The measurement of a single emitter is challenging due to the lack of suitable high-speed and sensitive photodetectors. Instead, it may be necessary to measure several emitters in parallel but other approaches are being explored.

  The chalcogenide nanoLED project made significant progress in the current period in understanding the underlying mechanism for bright electroluminescence emission at ambient conditions by pulsed electrical injection of WSe_2 monolayers. In period 10, the team will explore best approaches to couple these devices to antennas to enhance emission speed and efficiency. The team expects to fabricate and test antenna-coupled devices and demonstrate >50-time peak enhancement from WSe_2 in the next period. In addition, efforts to couple these chalcogenide nanoLED devices to waveguides will begin. The observed emission wavelength of 750 nm will require either an oxide or nitride waveguide for low loss. Moreover, careful structure and process design is required to ensure good waveguide coupling, minimal processing damage to the monolayer, and efficient electrical gating.

  The new project on incorporating colloidal quantum dots into the antenna-LEDs started in period 9 by the **Wu** group in collaboration with **Michael Bartl**, and will continue in period 10. A key research effort will be to increase the selectivity of quantum dot binding to the active nanoLED region. Currently, undesired binding let to some undesirable light emission outside of the slot region. This “off-slot” light emission will need to be reduced to enable measuring the spontaneous emission lifetime and determining the antenna enhancement of the spontaneous emission.

- *Coupling of nanoLEDs to Optical Waveguides:* The **Wu** and **Yablonovitch** will continue research on efficient coupling of the emission of antenna enhanced nanoLEDs to optical waveguides, which will be of great importance for integrated optical interconnects. Based on the simulation work in the current period, the team will start with fabricating an electrically injected waveguide-coupled antenna-enhanced nanoLED device. On the simulation side, a simple link will first be demonstrated with a large area photodiode with the same device structure as the nanoLED. However, to create a low capacitance photodiode, the device will need to be integrated with another material. This can be achieved by coupling light from the indium phosphide waveguide to a silicon waveguide in order to route the low capacitance photodiode.

- *Integrating nanoLEDs on Silicon:* This is a new project that will be started by the **Kim** group at MIT in close collaboration with the **Wu**, **Yablonovitch**, and **Chang-Hasnain** groups at Berkeley. While the antenna-enhanced nanoLED helps to satisfy the energy efficiency and small-scale requirements to replace the laser in future photonics, at this stage of the project, integration of nanoLEDs to Si CMOS has not been realized. The complexity of integration with nanoLED, waveguide and Si requires a novel innovation in semiconductor heterointegration. In recent years, the **Kim** group has developed a universal technique to transfer epitaxial films of compound semiconductors to be interfaced with Si CMOS. This new technology, referred as ‘two dimensional layer transfer’, relies on the use of graphene as a platform for semiconductor epitaxy. Based on this technique, epitaxial stack for the nanoLED device will first be grown on a graphene coated InP substrate, then transferred to a Si CMOS with a low-index material to help bond and define the waveguide for the nanoLED. Once the Si CMOS, cladding material and III-V stack has been integrated together, the III-V stack can undergo CMOS-friendly processes to fabricate the nanoLED. In period 10, the group aims to demonstrate (1) InP buffer layer grown on top of graphene suitable for growing the nanoLED epitaxial stacks, and (2) the feasibility of exfoliating and bonding the epitaxial buffer film on top of a Si substrate. The longer-term goal is to fabricate the antenna-enhance nanoLED on top of the transferred III-V epitaxial film with demonstration of wave-guide coupling.

2civ. *Theme IV: Nanomagnetics* *Theme Leader:* **Jeffrey Bokor** *(UC Berkeley)*

The nanomagnetics team consisting of the research groups of **Jeffrey Bokor**, **Sayeef Salahuddin**, **Vladimir Stojanović** (all *Berkeley*), **Shan Wang** (*Stanford*) and **Sakhrat Khizroev** (*FIU*) will continue research toward achieving an ultra-low energy magnetic switch operating at speeds of a few picoseconds, and energy-efficient magnetic switching using spin-orbit torque and nanometer-sized spin torque transfer magnetic tunneling junction devices. A more detailed description of period 10 nanomagnetics research plans is given below.

- *Picosecond Magnetic Switching and Integration with CMOS:* The **Bokor** group, in collaboration with the **Salahuddin** and **Stojanović** groups, will built on the significant progress in the current period on miniaturization of the magnetic GdCo and GdTbCo dots used for ultrafast switching. The defining goal for period 10 is the demonstration of an ultrafast magnetic memory including integrated switching using psec electrical pulses and electrical readout. Initially, the team will use the anomalous Hall effect as the electrical readout. They also plan to study the scaling of the threshold electrical switching current as a function of the size of the magnetic dot, with the goal to reach a switching current in the range of tens of micro-Amps. This is the critical range, which could be delivered by a single, minimum sized CMOS transistor. The ultimate goal remains the integration of ultrafast magnetic switching devices on CMOS, which would be a significant legacy achievement of the Center for E^{3}S. On the system-level side, the team will explore concepts to take maximum advantage of ultrafast magnetic devices by designing circuit and system level experiments aimed at finding optimum ways of exploiting ultrafast magnetic switching for practical applications.

- *Spin-Orbit Torque Switching:* The **Salahuddin** and the **Wang** groups will continue to investigate topological effects for energy efficient computing and spin orbit torque (SOT) switching and energy efficient computing. Regarding the latter, the **Salahuddin** group will start to leverage E^3S work in the last few years on the charge current control of small magnets for energy efficient learning machines. In more detail, period 10 research plans will include efforts on stochastic Boltzmann machines—an implementation of the Ising model with stochastic units. This work will be based on the demonstration that a conventional transistor coupled with a properly designed SOT magnetic tunnel junction (MTJ) device could be used to implement the stochastic units (neurons) needed for the Boltzmann machine [32]. Here the SOT is used to bias the stochastic switching of the magnet, which allows for the 'weighting' of the resistance seen through the MTJ. The group will work on SOT devices to reduce the current needed to deflect magnetization, which will reduce the power consumption while being used as a stochastic neuron. In addition, the potential of using anti-ferromagnets in the SOT device will be examined. The main motivation is to increase the speed of stochastic flip-flopping of the magnetic order, which, for an antiferromagnet, can be two orders of magnitude higher than for a typical ferromagnet. This will reduce the 'correlation time', i.e., the time needed for the Boltzmann machine to complete one cycle of computation.

  The **Wang** group plans to perform experiments to demonstrate SOT switching of adjacent ferromagnets, especially MTJ-compatible CoFeB and NiFe materials, in the SmB6 and heavy metal systems. The size dependent switching behavior (down to 10 nm), fast switching (< 1 ns), multilevel switching, and possible field-free switching will be investigated. Furthermore, the group plans to improve perpendicular magnetic anisotropy (PMA) of adjacent ferromagnets. PMA is a parameter determining the thermal stability of a single SOT-MRAM cell device and thus its integrated density. PMA is currently very weak and not practicable in topological material systems. Finally, combining SOT and perpendicular VCMA for logic in memory and energy efficient AI hardware applications will be explored.

- *Magnetic Tunneling Junction Devices:* Based on the successful demonstration of spin torque transfer (STT) MTJ devices with incorporated ~2 nm $CoFe_2O_4$ nanoparticles, in period 10, the **Khizroev** group plans to build a complete STT-MTJ device capable of multilevel signals in which spin polarized currents are used both for writing and reading. For this, STT-MTJ devices will be built from non-traditional materials, which will be better suited for the proposed 3D configuration. The traditional STT-MTJ stack is made of two CoFeB layers separated from each other by a thin layer of MgO. A challenge with integration of this traditional composition into the proposed 3D configuration is the maintenance of the perpendicular magnetic anisotropy in all the magnetic layers of the large stack. Therefore, the proposed STT-MTJ device will be built entirely out of Co/Pd and Co/Pt pairs. These pairs have shown a strong perpendicular anisotropy due to the surface interface. Previously, the **Khizroev** group has demonstrated both GMR/TMR effects and STT switching in these structures. MOKE will be used to study the multilevel signal information in the STT-MTJ devices.

2cv. *System Integration* — *Leader:* ***Vladimir Stojanović*** *(UC Berkeley)*

The System Integration team led by **Vladimir Stojanović** (*UC Berkeley*) will continue its important role of connecting with all four research themes in its role as "control organ", checking that the component research outcomes and new scientific device concepts of the Center will actually lead to new energy-efficient system architectures, enabling future ultra-low power information technologies.

In period 10, the **System Integration** group will continue research into system integration of E^{3}S nanomechanical and nanomagnetic devices since they may offer the opportunity for inherent non-volatility, which may fundamentally alter the balance between computing, communication, and storage for a given application. The goal is to provide both a path to quantifying the benefits of the emerging device technologies at the circuit/system level as well as guidance to the device designers on which device design parameters are critical to improve from the system level perspective. In this context, the project aims to create modeling and optimization methodology that connects the device parameters to the circuit and system-level metrics. The plan is to develop alternative system implementations, exploiting such non-volatility across circuit, micro-architecture and architecture levels, and thus quantify the degree to which it can provide benefits in a full application.

In addition, the **Stojanović** group will explore integrated circuit implementations of the systems in the so-called “edge compute” scenarios since the sensory and computation functions are severely energy limited in such systems. Deep neural networks have recently emerged as a very efficient computational alternative to the standard classification algorithms, and the one that is flexible enough to warrant an implementation using specialized digital functions, and still be usable in a variety of sensing scenarios. The group has focused on hardware macros that support efficient implementations of fully-connected and convolutional layers with enough re-configurability to allow mapping of various popular networks. At the same time they introduce algorithmic modifications (such as permutation-based transforms/pruning and smart quantization) to allow mapping of these highly irregular computations onto regular in-memory structures implemented with non-volatile memory relays and spin devices. Setting-up these efficient microarchitectures will enable to evaluate various device flavors in a very structured and well confined architecture context that focuses on efficiency of local storage and computation without large control overheads that usually obfuscate the gains obtained from the raw device performance.

The accelerator generator framework, which E^{3}S **System Integration** has put in place during the previous year, will now serve as the baseline for the generation of new designs utilizing the nanomagnetic and nanomechanical devices, as well the tool for benchmarking of their performance vs. CMOS-only designs. Being able to quantify the application-level benefits of these emerging device technologies will hopefully both help stimulate the interest in their adoption (and further process developments required to support it), as well as provide important guidance to E^{3}S researchers on the critical device design parameters that need to be further optimized in the context of the given application and architecture. The group will therefore conduct a detailed study of the use of nanomechanical switches as nonvolatile local memory blocks, lookup table computational elements as well as reconfigurable interconnects in these architectures. Focus will also be aimed at benchmarking of fast nanomagnetic devices and propose digital designs based on these devices that fit well within the accelerator chip architecture.

Development of the embedded system generators for high-value ubiquitous application macros for “edge computing” scenarios, enables the transfer of knowledge and technology as well as the encapsulation of new technologies. It is also a key benchmarking tool, which motivates adoption by evaluating the value-add of the new technologies at the application level. The framework E^{3}S is developing will allow evaluation of the cross-layer performance that future device technologies need to fulfill to make relevant gains in these critical applications.

III. EDUCATION

1a. *Goals and Objectives*

The primary element of the Education goal is the training of Ph.D.- and M.S.-level scientists and engineers in energy efficient electronics science who: 1) are knowledgeable in the scientific approaches to energy efficient digital electronics systems; 2) understand that working in diverse teams enhances creativity; and 3) understand the process of innovation, entrepreneurship and the transition of research results to commercially viable products. In addition, the Center also aims to prepare high school and undergraduate students to pursue studies and research in the energy efficient electronics field to increase the number of students pursuing technical disciplines, contributing to an engaged, skilled and diverse technical workforce in energy efficient electronics science. The Center integrates research and education to stimulate and prepare students and postdocs to pursue careers in energy efficient electronics science.

The 2018 E^{3}S Annual Retreat included a breakout session on Education and Legacy. Led by Associate Director for Education, **Lea Marlor**, the Center members reaffirmed the Education strategy that builds on the development of a pipeline of undergraduates who will be interested in research and graduate education. Developing online training materials on the Center's research has continued to be emphasized in the Center's second five years and will serve as the venue to establishing the Center's Education legacy.

1b. *Performance Metrics*

In the current strategic plan, the following indicators are used to measure the Center's Education performance:

Table 3.1.

Objective	Metrics	Frequency	Targets
Education	Center graduates completed E^{3}S training	Yearly beginning in Period 3	Period 2: Baseline Periods 3-5: 50% Period 6: 15% Period 7: 30% Period 8: 40% Period 9: 50%
	Students and postdocs participating in education and diversity programs *(discontinued in the 2nd five years)*		
	Students accessing online courses of the Center *(new)*	Yearly beginning in Period 6	Period 6: 0 Period 7: 15 Period 8: 0 Period 9: 15
	Undergraduates who pursue advanced degree in science and engineering	Yearly beginning in Period 3	Period 3: 5% Period 4: 30% Period 5: 35% Period 6: 40% Period 7: 45% Periods 8-9: 50%
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Yearly beginning in Period 3	Period 2: Baseline Period 3: 5% Periods 4-5: 80% Periods 6-9: 85%

	Pre-college students who pursue a bachelor's degree in science and engineering	Yearly beginning in Period 3	Period 3: Baseline Periods 4-5: 70% Periods 6-9: 80%
	Students and postdocs serving in leadership roles in the Center	Yearly beginning in Period 2	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Periods 6-8: 30% Period 9: 20%

In the E^3S Strategic Plan 2015-2020, the organization of metrics for Education and Diversity changed. Three metrics that measure the progression of students in the pipeline are now tracked under Education, while metrics for the underlying demographics are tracked under Diversity. One metric on graduate student and postdoc participation the Center's activities was dropped, given that the participation is organized under the E^3S Leadership Program.

1c. Problems Encountered

Much of the efforts in period 9 were devoted towards the legacy of the education efforts for after the Center sunsets. Center staff have been preparing and submitting proposals with the goal of having continued funding for the education programs once the Center is no longer funded. While we are currently waiting to hear the decisions on these funding opportunities, the Center continues its efforts to find new sources for these programs.

2. Educational Activities

During period 9, the Center graduated nine graduate students and six postdocs. In addition, eight undergraduates who were research interns with the Center, either through one of the REU programs (E^3S REU or ETERN) also received their baccalaureate. To date, E^3S has graduated 180 graduates (70 undergraduates, 69 graduates, and 49 postdocs). These students and postdocs have gone on to pursue careers in industry, academia, and national research laboratories around the globe (see Graduates Table, Centerwide Output). These Center alumni have benefited from the Center's formal and informal training programs and opportunities.

Since the start of the Center, E^3S Director, **Eli Yablonovitch** has been teaching biennially a graduate level course on low energy electronics with a strong focus on E^3S topics and perspectives. In Period 9, the course, a listed UC Berkeley course, was taken by four graduate students from two of the five E^3S member institutions.

The Center also offers a variety of informal training opportunities for graduate students and postdocs including: presenting, both oral and poster, at seminars and during Center events; mentoring of undergraduates; group analysis of competing research; participating in the REU intern selection process; serving a poster judges, and conducting scientific demonstrations at outreach events. In period 9, 35 graduate students and seven postdocs took advantage of these practical training opportunities.

These informal training opportunities are part of the professional development opportunities of the Center. Given the number of opportunities available, the Center has also developed the E^3S Professional Development Program (E^3S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences. Upon completing enough areas, a student/postdoc will receive a Leadership Certificate. Thus far, 24 students have earned a certificate of completion, of these, five were awarded in period 9. More than half, 41 (51%) of the E^3S students participated in a training area in period 9, with 38 (48%) having completed at least one area.

The Center also offers training in areas that it deems important in developing a scientist /engineer. All mentors of REU students receive training in project management and interactions between mentor and mentee. In period 9, 25 students and postdocs received training in these area.

The recent 2018 survey of graduate students and postdocs identified the impact of the Center's education programs on increasing the respondents' understanding of low energy consumption device science and technology (Figure 3.1). Students also indicated that the Center has positively impacted their professional development and interests in energy efficient electronics (Figure 3.2).

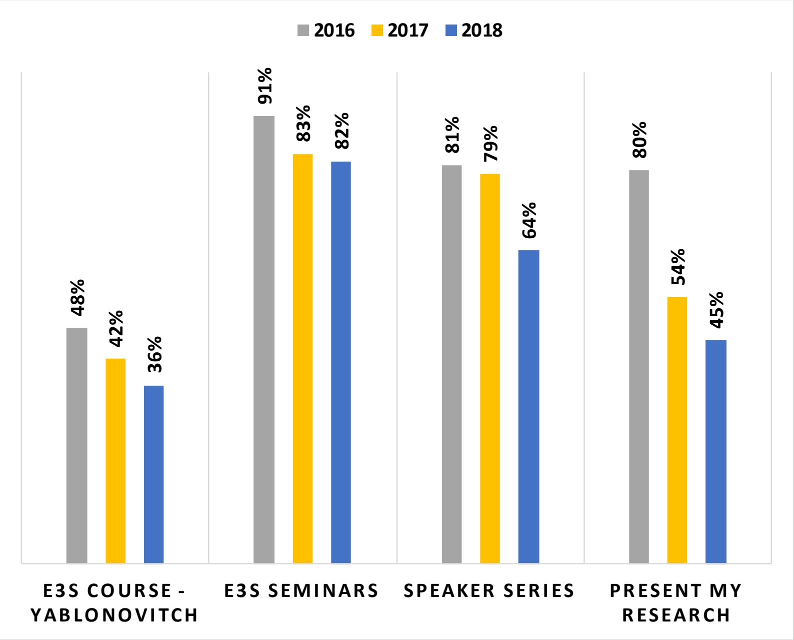


Figure 3.1. Graduate students and postdocs indicated the Center's educational activities are sharpening their understanding of low energy consumption device science and technology.

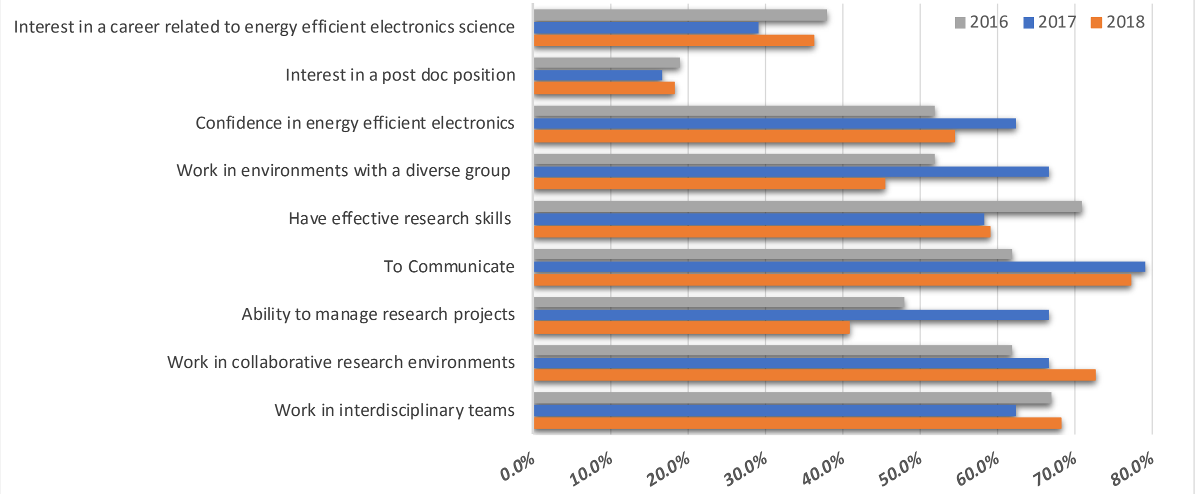


Figure 3.2. Graduate Students and postdocs indicated that the Center has positively impacted their professional development and interests.

The Center is also impacting undergraduate education by offering research opportunities. Students of the member institutions participate in the ETERN program that offers paid 10-week internships during the academic term. In period 9, there were two ETERNs at FIU and UTEP.

The Center also manages three REU programs for undergraduates from 4-year institutions and community colleges. Six community college students and 12 undergraduates from 4-year institutions were hosted in E^{3}S or E^{3}S affiliated research groups at MIT and Berkeley. In alignment with the Center's focus community college education, four E^{3}S faculty supported the professional development of five community college faculty in period 9 with the goal of enhancing STEM classroom instructions. Two community college professors developed teaching materials for an introductory engineering courses. One community college professor developed teaching materials for an energy systems course. The remaining two community college instructors are continuing to develop their curriculum based on the work they did over the summer.

The following sections provide details supporting the above summary of the state of education in period 9.

2a. Internal Educational Activities

The internal educational activities that were initiated in previous reporting periods continued in period 9. Seminars, external speaker series, poster sessions, and the Center's Annual Retreat are all informal education venues for undergraduates, graduate students and postdocs. The research internship program, ETERN, for early engagement of undergraduates involved two interns conducting research during the academic terms at two institutions.

Table 3.2.

Activity Name	E^{3}S Research Seminars
Led by	**Michael Bartl** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 267 Undergraduate Students: 2 UTEP, 1 FIU Graduate Students: 100 Berkeley, 14 MIT, 2 Stanford, 12 UTEP, 1 FIU Postdocs: 37 Berkeley, 12 MIT, 7 Stanford, 5 FIU, 2 UTEP

The E^{3}S seminars serve as a vehicle to share the research being undertaken at the Center across research themes and member institutions, as well as an educational forum. The speakers are mainly graduate students and postdocs, who present the progress of their research. Occasionally, E^{3}S faculty present new projects, and industry partners have presented the research efforts in their company. Period 9 is expected to conclude with 12 seminars; a list of scheduled seminars can be found at this website: https://e3s-center.berkeley.edu/news-events/seminars/. For attendance at the seminars, please see Appendix D.

Table 3.3.

Activity Name	Seventh Annual Retreat & Poster Session
Led by	**Eli Yablonovitch** (Berkeley)
Intended Audience	Faculty, Staff, Students, Postdocs, Industry Partners & Programmatic Partners
Approx. Number of Attendees (if appl.)	Total – 69 Undergraduate Students: 1 MIT, 1 UTEP Graduate Students: 21 Berkeley, 1 MIT, 1 FIU, 2 UTEP Postdocs: 8 Berkeley, 3 MIT, 1 Stanford

The Annual Retreat has continued to be a multi-purpose venue. One purpose is to educate graduate students and postdocs through two days of presentations and discussions. Part of the education is the opportunity to present one's research at a poster session attended by representatives of member companies. There were 20 posters at the 2018 Annual Retreat presented by 2 undergraduate students (1 MIT, 1 UTEP), 12 graduate students (8 Berkeley, 1 FIU, 2 MIT, 1 UTEP), 6 postdocs (3 Berkeley, 2 MIT, 1 Stanford). For a list of posters, please see Appendix K.

Table 3.4.

Activity Name	Poster Presentation at the External Advisory Board Meeting
Led by	**Michael Bartl** (Berkeley)
Intended Audience	External Advisory Board

Approx. Number of Attendees (if appl.)	Total – 11 Graduate Students: 8 Berkeley Postdocs: 3 Berkeley

This period, 11 students and postdocs were given the opportunity to present their research to the external advisory board.

Table 3.5.

Activity Name	Sixth Annual Student and Postdoc Retreat
Led by	**Lea Marlor** (Berkeley) and **Kedrick Perry** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 12 Undergraduate Students: 1 MIT, 1 UTEP Graduate Students: 2 Berkeley, 2 UTEP, 1 FIU Postdocs: 3 Berkeley, 1 MIT, 1 Stanford

In September, the Center hosted its 7th Annual Student and Postdoc Retreat for graduate students and postdocs. Topics discussed were the E^3S Rotation Program, the Graduate Student and Postdoc Council, ways to increase attendance at future student retreats, and the NSF Professional Development workshop.

Table 3.6.

Activity Name	E^3S Internship (ETERN)
Led by	**Kedrick Perry** (Berkeley)
Intended Audience	Undergraduate students at Center’s institutions
Approx. Number of Attendees (if appl.)	Total – 2 Undergraduate Students: 1 FIU, 1 UTEP

The ETERN program is an academic-year program for undergraduates at all of the Center’s institutions. The primary goal is to attract students to energy-efficient electronics science by providing research experiences to lower-division undergraduate students of member institutions. The major aim is to enhance the pipeline of students interested in graduate studies in the science and engineering disciplines of relevance to the Center. In period 9, we had 2 participants. These students were advised by E^3S faculty and mentored by E^3S graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs such as research seminars.

Of our ETERNS, 86% (12) have completed a four-year degree in an E^3S related major. Eight are currently enrolled in graduate school (for STEM and all at E^3S institutions). Cumulatively, 36% (5) are underrepresented minorities and 36% (5) are female.

Table 3.7.

Activity Name	E^3S Rotation Program
Led by	**Michael Bartl** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 2 Graduate Students: 2 UTEP

The Center allows for its graduate students and postdocs to go to a partner institute, different from their home university to conduct research for a period of time. This year, two students spent their time doing research at UC Berkeley. **Aldo Vidana** (UTEP) and **Edgar Acosta** (UTEP) worked in Prof. **Tsu-Jae Liu**’s lab under the guidance of postdoc, **Sergio Almeida** in the summer of period 9. Both worked on projects on the 2D stritch.

2b. *Professional Development Activities*

The students and postdocs of the Center for E^{3}S can avail themselves of many professional development opportunities. In previous periods, we implemented training in ethics, diversity, entrepreneurship, project management, and mentoring. The Center has also developed the E^{3}S Leadership Certificate that students receive after completing enough areas in the Professional Development Program (E^{3}S PDP) with the goal of guiding the students and postdocs to acquire a diverse and balanced set of experiences.

Table 3.8.

Activity Name	E^{3}S Professional Development Program (E^{3}S PDP)
Led by	**Lea Marlor** (Berkeley)
Intended Audience	All Graduate Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 38 Graduate Students: 23 Berkeley, 6 MIT, 1 FIU, 3 UTEP Postdocs: 5 Berkeley

Students and postdocs are provided with a number of programmatic activities within the Center aimed at professional development. These programs offer different areas of development: leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship. E^{3}S PDP is a framework to ensure a student or postdoc receives well-rounded professional experiences (Appendix E). For a certificate of completion, students and postdocs must complete: 1) at least one activity in the area of leadership, outreach, or mentoring; and 2) at least one education activity in three other training areas (teaching, proposal writing, science communication, and entrepreneurship). Thus far, twenty-four students have earned a certificate of completion, of these, four were awarded in Period 9. Approximately half, 41 (51%) of the E^{3}S students started a training area by the end of Period 9, and 38 (48%) have completed at least one training area by the end of Period 9.

Table 3.9.

Activity Name	Project Management and Mentor Training
Led by	**Lea Marlor** (Berkeley) and **Kedrick Perry** (Berkeley)
Intended Audience	Graduate Student and Postdoc Mentors
Approx. Number of Attendees (if appl.)	Total – 25 Graduate Students: 15 Berkeley Postdocs: 10 Berkeley

As part of the Center's objective to provide leadership experiences, graduate students and postdocs who served as mentors in the Center's summer undergraduate and precollege programs participated in project management and mentor training. Students and postdocs received two hours of mentoring and project management training and then over 360 hours of hands-on practice in mentoring, supervisory skills, communication, and leadership. The project management training provided an overview of project management and included the following topics: importance of project management, project management defined, and steps in project management. The mentor training provided an overview of how to be a mentor and included the following topics: what is/is not mentoring, impact of effective mentorship, and mentoring in action. Mentor training also included training on how to work in diverse groups and with people from different backgrounds.

Table 3.10.

Activity Name	REU Selection Committee
Led by	**Kedrick Perry** (Berkeley)
Intended Audience	All Graduate Student and Postdocs

Approx. Number of Attendees (if appl.)	Total – 14 Graduate Students: 9 Berkeley, 2 FIU, 1 UTEP Postdocs: 2 Berkeley

Graduate students and postdocs are invited to review applications for the E^3S Research Experience for Undergraduates (REU) program. Each member of the selection committee reviews the application material, including personal statement, transcript, and letters of recommendations of ~5 applicants. Based on their review process, the postdocs and graduate students provided a list of applicants that should be considered for placement in a REU summer research project.

Table 3.11.

Activity Name	REU Poster Review
Led by	**Lea Marlor** (Berkeley)
Intended Audience	Undergraduate Students at Center's Institutions
Approx. Number of Attendees (if appl.)	Total – 17 Graduate Students: 13 Berkeley Postdocs: 4 Berkeley

The Center hosted three REU programs, one for upper division undergraduates, one for students attending an HBCU institution, and another for community college students in conjunction with an REU site award. In addition to the REU programs, the Center also hosted an RET program for community college faculty, also in conjunction with a site award. These programs concluded with a joint poster session of all REU and RET participants. This offered a professional development opportunity for graduate students and postdocs to be reviewers. In period 9, 17 graduate students and postdocs evaluated the posters based on the following criteria: presentation skills, poster layout, and content (problem, methods, results & understanding). Each member of the review panel evaluated 4-5 posters so that all of the summer students had two evaluations of their work. At the conclusion of the poster session, assessments were anonymously shared with the REU intern to provide them feedback on their performance.

2c. *External Educational Activities*

Table 3.12.

Activity Name	E^3S Teacher Fellows Program
Led by	**Lea Marlor** (Berkeley)
Intended Audience	Community College Professors
Approx. Number of Attendees (if appl.)	Total: 5

With the Center's focus on creating a pipeline of community college students who pursue a baccalaureate degree in science and engineering, it is imperative for the Center to engage community college faculty. These individuals can further integrate E^3S science and research findings into the community college curriculum and increase community college students' awareness and knowledge of low-energy electronic devices. In Period 9, the Center hosted five community college faculty members in our E^3S Visiting Faculty Program which allows a community college faculty to spend six to nine weeks in a research laboratory associated with the Center or develop curricula mentored by Center members. Leveraging a community faculty program that NSF awarded to the Center's PI, **Eli Yablonovitch**, E^3S Visiting Faculty participated in a pedagogy workshop that taught community college faculty participants about context-based and online teaching. The five E^3S visiting community college faculty are described below.

- **Velveth Klee**, a faculty member in the Department of Engineering at Los Angeles Trade Technical College (LATTC), one of the Center's education partners, was hosted by the Center as she developed course content for her engineering courses that is currently being implemented.
- **Leonard Filane**, a physics and math instructor at College of Marin, conducted nine weeks of curriculum development where he is in the process of creating a whole new course. This was a continuation of the work he did in the previous two summers and he continues to work with Berkeley faculty members to get the course accredited for students to transfer to a four-year school.
- **Thomas Sanford**, an engineering instructor at West Valley College conducted his 8-week project in Prof. **Vladimir Stojanovic**'s lab, and was mentored by postdoc **Rawan Naous**. **Mahnaz Firouzi**, an engineering instructor at Diablo Valley College, worked in Prof. **Eli Yablonovitch**'s lab, and was mentored by postdoc **Luis Pazos-Outon** and graduate student **Zunaid Omair**. These two professors have implemented their projects into an Introduction to Engineering course and an Introduction to Energy Systems course. **Jamie Kulp**, a chemistry instructor at Santa Rosa Junior College, worked in Prof. **Junqiao Wu**'s lab, and was mentored by postdoc **Sara Fathipour** and he is still working towards implementing his project.

Table 3.13.

Activity Name	E^{3}S E-book
Led by	**Tsu-Jae Liu** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx. Number of Attendees (if appl.)	Total: 4 (Theme Leaders)

The E^{3}S E-book is a legacy development in period 7. The book will discuss E^{3}S research and be written at a high school level. Each research theme has a dedicated section within the book, with the theme leaders deciding the subjects and chapters within each section. At the end of Period 9, each theme leader will produced an outline for their section. Graduate students and postdocs have worked to create the content for the book in period 9, and currently Theme 2 has created a first draft for its section.

Table 3.14.

Activity Name	Cal Day
Led by	**Aine Minihane** (Berkeley)
Intended Audience	The San Francisco Bay Area Community
Approx. Number of Attendees (if appl.)	Total- 2 Graduate Students: 2 Berkeley

Each spring, Berkeley opens itself to the public to showcase what is done on campus for the general population. This year **Aine Minihane** led two students in demonstrating how 2D materials (graphene) conduct electricity. More senior participants were also introduced into the Center's goal of using 2D materials to tackle the energy efficiency problems faced in our current electronics. Approximately 350 people participated in the E^{3}S demonstration.

2d. *Integration of Education and Research*

Research is the driving force behind all of our educational programs and activities. As in previous years, the Center continues to integrate its research mission into its educational programs. This level of integration is interwoven into the Center's curriculum, videos, hands-on demonstrations, research seminars, and presentations topics. We also use a vertical model, where faculty are mentoring postdocs and graduate students, postdocs and graduate students are mentoring undergraduates, and undergraduates are mentoring pre-college and K-12 students through the Center's outreach programs.

2e. Performance Against Metrics

During this reporting period, the Center has compared the educational programs with the period 9 targets. The table below displays these data and future metrics to measure education success.

Table 3.16.

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Education	Center graduates completed E^{3}S training	P2: Baseline P3-5: 50% P6: 15% P7: 30% P8: 40% P9: 50% P10: 15%	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)	5 (36%)	3 (23%)
	E3S graduate students taking online course taught by Center director	P6, 8, 10: 0 P7, 9: 10	(new for P6-10)				0	8	0	6
	Undergraduates who pursue advanced degree in science and engineering	P3: 5% P4: 30% P5: 35% P6: 40% P7: 45% P8-P10: 50%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)	36 (69%)	41 (73%)	47 (70%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P2: Baseline P3: 5% P4-5: 80% P6-10: 85%	n/a	3 100%	6 100%	7 100%	6 100%	4 80%	4 60%	6 100%
	Pre-college students who pursue a bachelor's degree in science and engineering	P3: Baseline P4-5: 70% P6-10: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)	180 (47%)	TBD

	Students and postdocs serving in leadership roles in the Center	P2: Baseline P3: 15% P4: 20% P5: 25% P6-8: 30% P9: 20% P10:15%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)	14 (16%)	17 (21%)

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

2f. Education Activities in Period 10

Much of period 10 will be spent in continuing the established education programs and continuing in the creation and development of the Center's Education legacy. The Center is expecting to have a first draft completed of the e-book by the end of the period, and continued rewriting and editing will take place in Period 10.

IV. KNOWLEDGE TRANSFER

1a. Goals and Objectives

Knowledge transfer is at the heart of the Center for E^3S mission and vision to foster groundbreaking new science discoveries and fertilize new technologies. As a Science and Technology Center, E^3S considers knowledge transfer activities and outcomes a key metric of its success. Since its inception, the Center has recognized establishing partnerships as a key factor in accelerating research, education and outreach endeavors. At the same time, the Center has put significant efforts into sharing new knowledge with industry, academia and research labs. At the Center for E^3S, knowledge transfer is seen as a two-way street: Sharing its discoveries in the development of novel, highly efficient electronic technologies with various outside stakeholders, while bringing new knowledge into the Center by engaging with key players of various science and engineering disciplines and at different educational levels.

Within the Center for E^3S, knowledge is transferred openly between all partners as a cross-fertilization of ideas and projects. Knowledge transfer outside of the Center includes sharing of results and ideas with materials and device researchers, circuit designers, CAD software programmers, and manufacturers. On the education and diversity side, knowledge transfer aims to create opportunities for students at all levels by reaching out to education partners from K-12 to university level, organizations and initiatives to increase diversity in STEM fields, and potential employers of the Center's graduates (students and postdocs).

The main pillars of knowledge transfer at the Center for E^3S continue to be:

- Sharing the Center's research, education and programmatic activities and making all outcomes broadly accessible
- Acceleration of research and programmatic outcomes through collaborations with partners in industry, academia, and research labs
- Ensuring that Center outcomes are accessed and recognized as being impactful (as measured by citations)
- Alumni's of the Center's research and education programs continue to participate in the industries and technical disciplines with relevance to the Center
- Outreach to the general public to stimulate and broaden support for STEM education and research in fields related to the Center's scope

1b. Table 4.1. Performance Metrics

Objective	Metrics	Frequency	Targets
Knowledge Transfer	Center publications	Yearly	Periods 2-5: Yearly: 18 Periods 6-7: 25 Periods 8-9: 30
	External citations of publications *(cumulative)*	Yearly	Period 3: 10 Period 5: 100 Periods 6-9: 25% yearly increase
	Talks at peer-reviewed conferences *(added in Period 6)*	Yearly	Periods 6-7: 12 Periods 8-9: 15
	Center sponsored symposia & workshops	Yearly	Period 2: baseline Period 3: 0 Period 4: 1 Period 5: 0 Period 6: 2 Periods 7-9: 1
	Website hits & unique visitors *(discontinued)*	Yearly	Period 2: Baseline Period 3: 20% increase

	Contacts with industry • Talks & Meetings • Presentations by industry	Yearly	Period 2: 18 Period 3+: 36 yearly Yearly: 2
	Research Collaboration with industry	Yearly	Period 4: 1 Period 5: 2 Periods 6-7: 3 Periods 8-9: 4
	Patents Disclosures/Provisional	Yearly	Periods 3-4: 3 Period 5: 5 Periods 6-7: 2 Period 8: 3 Period 9: 4
	Patent Application Filed/Granted	Yearly	Period 4: 0 Period 5: 3 Period 6: 1 Periods 7-9: 2
	Center's alumni into relevant industries	Yearly	Period 5: 50% Periods 6-7: 30% Periods 8-9: 40%
	Center's alumni pursuing research in disciplines related to the Center at academia & research labs *(added in Period 6)*	Yearly	Periods 6-9: 30%
	Technology development attributable to Center's research • Low energy devices • Enabling other applications	Yearly	Periods 6-7: 0 Periods 8-9: 1
	• Number of external articles on the Center *(discontinued)*	Yearly	Period 3: 100% increase Period 5: 50% increase

1c. *Problems Encountered*

Nothing to report.

2a. *Knowledge Transfer Activities in Period 9*

In period 9, the Center has continued its strong record of knowledge transfer. This was achieved by a range of activities, including disseminating results and outcomes from research and education, by organizing national meetings and workshops, by engaging various stakeholders (from academia to industry), and by using social media and other new platforms to reach a broad community of scientists and engineers, attract new students into the Center and reach out to the general public.

2018 STC Directors Meeting

This year, the Center for E^{3}S was selected to organize the 2018 STC Directors Meeting. With permission from NSF, this year's meeting was held at the UC Berkeley campus on August 21-22. As topic for this meeting we chose "Engaging Diverse Audiences: Broadening Participation through Science Communication", recognizing the increasing importance of communicating science and engineering to a broad community. The meeting featured presentations form invited speakers, panel discussions, video presentations, a tour of the San Francisco Exploratorium, and several general networking opportunities (see Appendix H for detailed program). We assembled an exciting line-up of speakers and panelists, all experts in various aspects of science communication, including:

Nsikan Akpan, Digital Science Producer, *PBS NewsHour*
Peter Aldhous, Science Journalist, *BuzzFeed News*
Carol Lynn Alpert, Director, Strategic Projects Group, *Museum of Science, Boston*
Caleb Cheung, Director of Education, *Chabot Space & Science Center*
Jennifer Frazier, Program Director, Living Systems, *Exploratorium, San Francisco*
Erika Check Hayden, Director, Science Communication Program, *UC Santa Cruz*
Todd Ostomel, Senior Patent Counsel, *Squire Patton Boggs*
Cynthia Phillips, Office of Integrative Activities, *National Science Foundations*
Patricia Raun, Director, Center for Communicating Science, *Virginia Tech*
Aditi Risbud, Director for Marketing and Communication, *UC Davis*
Seth Shostak, Senior Astronomer and Director, Center for SETI Research, *SETI Institute*

The meeting attracted 125 registered attendees and brought together leadership teams from all 12 current STCs in the country with five NSF program directors and officers. In addition, with supplement funding from the NSF we were able to bring thirty students from current STCs to the Berkeley campus to participate in the meeting as well as in several professional development activities focused on various aspects of science communication, such as:

- Media Training Workshop, **Sarah Yang**, Executive Director, COE Marketing/Communications, UC Berkeley, **Roxanne Makasdjian**, Director of Broadcast Communications, UC Berkeley
- Career Panel: “The Path from Scientist to Science Communicator”, **Aditi Risbud**, Director for Marketing and Communication, UC Davis
- Improvisation Workshop: “Communicating science: Learning to listen, listening to learn”, **Patricia Raun**, Director, Center for Communicating Science, Virginia Tech
- Diversity & Inclusion Workshop: “Increasing diversity and inclusion in science and engineering” **Kedrick Perry**, Diversity Director, Center for E^{3}S, UC Berkeley
- Visit and Tour of the San Francisco Exploratorium, **Jennifer Frazier**, Program Director, Living Systems, Exploratorium, San Francisco

The feedback received from attendees and NSF personnel was very positive. In particular, attendees positively noted that the meeting topic, invited speakers, and general organization of the meeting.

Dissemination of Results

In this current period, the Center for E^{3}S has continued its strong dissemination record as one of its key knowledge transfer avenues. These efforts have been broadly supported by all of the Center’s researchers and key staff personnel through publications in scientific peer-reviewed journals, presentations at peer-reviewed conferences, scientific meetings, universities and industry, and knowledge exchange with a wide range of communities via public and private meetings.

So far in this period, the Center has published 23 papers in journals, and additional six are under review. In addition, papers from 21 talks, have been presented at peer-reviewed conferences, or have been accepted. Center members also presented an additional 31 talks and 13 posters at other scientific conferences and meetings.

The Center for E^{3}S has recognized online content and social media as increasingly important knowledge transfer vehicles. The re-designed Center website (https://e3s-center.berkeley.edu/) and updated content (finished in period 8) was designed both to keep E^{3}S members informed on all Center aspects and to serve as a major recruiting tool for new students. Recruiting and general outreach activities are further supported by our social media presence (E^{3}S Twitter and Facebook sites) as well as a blog site. The Center for E^{3}S Blog Site features a variety of blog entries from Center members including the Center staff and students and postdocs. Blog entries are open to the public and are an excellent avenue to keep Center members, affiliates, prospective students and postdocs, as well as the general public informed about issues related to energy efficient electronics.

In addition, the Center has continued to transfer to knowledge to industry and seek input from our Industrial Research Board (Applied Materials, HP Enterprise, IBM, Intel, and Lam Research) and other companies the Center considers key players in low-energy electronics. Interactions occurred at multiple levels, including seminars by invited external speakers, Center students and postdocs visiting companies to learn about other low-energy electronics programs, and co-sponsorship of and participation in the BETR (Berkeley Emerging Technologies Research) Center's biannual meetings.

Center Legacy Initiatives

Since the E^{3}S renewal in fall 2015, the leadership of the Center has recognized the importance of developing a continuing Center legacy. Led by Center director, **Eli Yablonovitch**, the Executive Committee has prioritized the establishment of a strong and lasting research and education legacy. Since October 2017, the development of legacy programs has also become a compulsory part of E^{3}S internal proposals. All E^{3}S investigators are required to submit plans for legacy development as part of their annual funding requests. In addition, the Center considers the development of a strong education and diversity legacy of equal importance to a strong research legacy. In the last eight years, E^{3}S has established several outstanding education and diversity initiatives. Current efforts are devoted to finding strategic partners and to secure external/independent funding to keep the most successful programs running past the lifetime of the Center.

With input from the E^{3}S External Advisory Board and the E^{3}S Industrial Research Board, the leadership team of the Center for E^{3}S concluded that pursuing different paths for the different E^{3}S research themes is the most successful approach toward the development of strong and lasting legacy programs. The different themes represent different levels of technological maturity, and they will need to evolve separately after incubation in E^{3}S.

Thus far, the Center has several continuing research initiatives and programs established and/or initiated:

Berkeley Emerging Technology and Research (BETR) Center. The BETR Center was established in 2016 with the goal to create a hub for physical electronics research at UC Berkeley. This Center is led by E^{3}S Nanomechnics Theme leader **Tsu-Jae King Liu** and includes six additional E^{3}S investigators as members. BETR's goal is to form interactions with companies for long-term research collaborations and knowledge transfer. Corporate sponsors gain early access to innovative ideas and research results, while university researchers gain insight into challenges faced by industry. Current BETR industry members include Applied Materials, Atomera, Lam Research, and SK Hynix.

Negative Capacitance Industry-Supported Center. This industry-supported center at UC Berkeley is based on research developed by E^{3}S investigator **Sayeef Salahuddin** in the first few years of the Center for E^{3}S. It was discovered that negative capacitance in ferroelectric materials can be used for low-power memory and switching applications. The negative capacitance industry-supported center will continue to pursue these goals with industry partners, including Intel, TSMC, and GlobalFoundries.

Graphene Nanoribbons MURI. The Carbon-based Hierarchically Integrated Synthetic Electronics (CHISEL) MURI with UC Berkeley as lead organization was established in 2016 with funding from the Office of Naval Research. This MURI is based, in part, on E^{3}S research on graphene nanoribbons (GNRs) and it explores their use to build complex electronic nanostructures. E^{3}S deputy director, **Jeffrey Bokor**, and E^{3}S investigators **Steven Louie** and **Felix Fischer** are part of the MURI team.

Semiconductor Research Corporation (SRC) JUMP Centers. Of the six current SRC JUMP Centers, E^{3}S investigators are part of two centers: ASCENT (Applications and Systems driven Center for Energy-Efficient Integrated NanoTechnologies) and ComSenTer (Center for Converged TeraHertz Communications and Sensing). **Jeffrey Bokor**, **Sayeef Salahuddin**, and **Shan Wang** are part of the

ASCENT Center, working on spintronic switching, whereas **Vladimir Stojanovic** and **Alon Elad** are members of the ComSenTer Center, focusing on high-speed circuits and systems.

Nanophotonics NSF ERC Proposal. Under the lead of E^3S Nanophotonics Theme leader **Ming Wu**, several E^3S investigators (including **Yablonovitch**, **Chang-Hasnain** and **Stojanovic**) have joint forces in developing an NSF Engineering Research Center (ERC) proposal. The research focus of the proposed ERC is on intelligent 3D sensing and imaging. If funded, this ERC will continue the strong E^3S legacy in nanophotonics, particularly the innovative antenna-LED approach.

Research Legacy on Future Technology. In addition to a legacy represented by continuing research organizations, E^3S prides itself on the scientific influence it will continue to have on the future science and technology of energy efficient electronics. For example, Theme 1 has found that tunnel-field effect transistors will be much more challenging to create, than expected. Nonetheless, Theme 1 has laid out the requirements that will guide future research, including atomic scale perfection, and non-Lorentzian spectral lineshape, with organically synthesized graphene nanoribbons as the material base. Theme 2 has demonstrated the importance of molecular functionalization on the surfaces of NEM switches that will likely become standard in the field of nanomechanics. Theme 3 has shown that the antenna-LED is the missing link of optoelectronic sources for on-chip optical communication. The antenna-LED operates at low power, but at a speed faster than lasers. Theme 4 has shown the correct path for high-speed magnetic switching, increasing switching speed by 100 times, down to the picosecond range.

E^3S e-Book and nanoHUB Website. At the beginning of this period, the Center for E^3S established its own website on the nanoHUB.org platform. Currently, content is produced and we expect the site to go live early next year. Highlights of this site will include educational videos featuring Center research topics targeting various educational levels (from high school to graduate level). In addition, the site will host the E^3S open-access e-book on energy efficient electronics written by E^3S faculty, postdocs and students. The objective of the e-book is to develop a comprehensive educational resource on energy efficient electronic science (including nanoelectronics, nanomechanics, nanophotonics, and nanomagnetics). The main goal is to motivate high school students to pursue academic studies and careers in the STEM fields. The e-book project has made significant progress and the section on nanomechanics is already completed. It is currently reviewed by high school and community college students and faculty, and we anticipate making the nanomechanics section available to the public in spring 2019. The other three sections are currently in progress and will be completed by sunset of the Center in 2020.

TTE Renewal Grant and Third-Party Support. The Transfer-to-Excellence (TTE) Research Experience for Undergraduates (REU) program was developed in the Center for E^3S with the goal to reach out to students at the California Community College (CCC) system. This program was so successful that NSF provided additional funding through a separate REU grant that expanded the research topics to various areas in engineering and science. We are delighted to report that we were just informed by NSF last month that this additional REU grant was renewed for another three years, and therefore, will enable E^3S to continue the TTE REU program beyond the sunset of the Center for E^3S (in 2020). Furthermore, we are currently working with other Centers on campus who have shown an interest to implement the TTE REU concept in their educational programs. For example, this summer the Center for E^3S has integrated five students from an NIH-funded center (PI Doudna) into our TTE program.

TTE-2.0 Proposal. As part of the Nanophotonics NSF ERC proposal application (see above), a new TTE program was proposed: “TTE-2.0”. In addition to providing research experience for students eager to transfer to a 4-year college, the proposed TTE-2.0 model will target the large portion of Community College students seeking primarily a first-class education and training to obtain the technical skills needed to enter the job market with an Associate Degree. The proposed program will provide students two consecutive summers of research experiences. The first summer will be a traditional REU stay at the UC Berkeley campus. In their second summer, students will perform a research internship at one of the ERC industry partners. This “second-bite-of-the-apple” research experience will be a tremendous opportunity for all

California Community College students, regardless whether their goal is transfer to a 4-year college or transfer to industry with an Associate Degree.

A more detailed account of the Center's knowledge transfer activities is given below.

- *Dissemination of Results*

  Dissemination of research and education results by E^{3}S researchers (from our REU summer undergraduate students to graduate students, postdocs and faculty) through publications in peer-reviewed journals and at scientific conferences has continued to be the main knowledge transfer venue.

  Table 4.2. Dissemination of the Center's Research Results in Peer-Reviewed Journals

Led by	**E^{3}S Faculty**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford	Palo Alto, CA
4.	UTEP	El Paso, TX
5.	FIU	Miami, FL

  So far in this reporting period, the Center's faculty, postdocs, students, and staff have published 29 papers (including six submitted manuscripts), all in peer-reviewed journals (excluding peer-reviewed conference proceedings). An important performance metric included in the Strategic Plan is the number of citations of the Center's publications. By the submission of this report the cumulative external citation count for the 188 published journal papers of the Center was 6076, an increase of 40 percent from last year.

  Table 4.3. Dissemination of Research via Proceedings of Peer-Reviewed Conferences

Led by	**E^{3}S Faculty**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford	Palo, CA
4.	UTEP	El Paso, TX
5.	FIU	Miami, FL

  So far in period 9, 21 talks by researchers from all E^{3}S member institutions were published in conference proceedings, including IEEE International Electron Devices Meeting, CLEO, and IEEE Photonics Society Conference.

  Table 4.4. Presentations by Center REU Alumni at Peer-Reviewed Conferences

Led by	**Lea Marlor, Kedrick Perry**
Organizations Involved	

	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	SPIE Photonics West	San Francisco, CA
4.	American Institute of Chemical Engineers (AIChE) Annual Conference	Pittsburgh, PA
5.	Council on Undergraduate Research (CUR) Symposium	Alexandria, VA
6.	SACNAS Annual Conference	San Antonio, TX

All alumni of the Center's REU programs are strongly encouraged to present their summer research results at scientific conferences. These conference trips are fully supported by the Center. So far, in period 9, four students presented their work at the SACNAS Conference in October in San Antonio, one student presented at the Council on Undergraduate Research (CUR) Symposium, one student presented at AIChE Conference, and one additional student will present at the upcoming SPIE Photonics West Conference.

Table 4.5. Granted Patents & Patent Applications

Led by	**E^{3}S Researchers**	
Organizations Involved		
	Name	*Address*
1.	FIU	Miami, FL
2.	MIT	Cambridge, MA

So far, in period 9, two new patents have been granted to E^{3}S researchers at MIT and FIU (one from Theme II and one from Theme IV).

Table 4.6. 2018 STC Directors Meeting

Led by	**Eli Yablonovitch, Jeffery Bokor, Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	UTEP	El Paso, TX
4.	FIU	Miami, FL
5.	The full list of attendees and their organizations is given in Appendix H	

The 2018 STC Directors Meeting was organized by the Center for E^{3}S and was held at the UC Berkeley campus August 21-22. The event brought together 125 registered attendees, including the leadership teams, students and postdocs from all 12 current STCs in the country, five NSF program directors and officers, and 16 invited speakers from TV, radio, news outlets, science museums, and academia. The program featured invited presentations and panel discussion about a wide array of science communication together with technical presentations from directors of all twelve current STCs (see Appendix H for the full meeting program). E^{3}S executive director, **Michael Bartl** (*Berkeley*) led the organization of the event, and, together with Center director **Eli Yablonovitch** (*Berkeley*), acted as co-chair of the STC Directors Meeting.

Table 4.7. WITI Gender Bias in Tech Workshop

Led by	**Kedrick Perry**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Stanford	Palo Alto, CA
3.	San Jose State University	San Jose, CA
4.	CITRIS	Berkeley, CA
5.	Samsung	San Jose, CA

The Center for E^{3}S joined forces with Women in Technology Initiative (WITI) in organizing the inaugural Gender Bias in spring 2018 (Appendix I). WITI was formed through a collaboration by CITRIS & the Banatao Institute and UC Berkeley's College of Engineering (**Tsu-Jae King Liu** and **Camille Crittenden**, both *UC Berkeley*). The mission of WITI is to promote and sustain the career growth of women technologists, increasing access to a range of technology workplace settings, facilitate and document improvements within companies, and coordinate with the top educational institutions that supply talent to the tech industry in Silicon Valley. E^{3}S diversity director **Kedrick Perry** co-organized the inaugural workshop, which focused on gender bias in technology and provided a virtual reality experience on what it is like to be a young female coder in a male-dominated startup environment. Interest in this workshop was strong and all 36 available spaces were filled quickly. Follow-up workshops are planned.

- *Broader Impacts of the Center's Research Outcomes*

  As an NSF Science and Technology Center, the Center for E^{3}S continues to seek opportunities of transferring knowledge acquired in its research projects to other organizations, including industry, research labs, and academia. Below are more details of the most successful transfer activities.

Table 4.8. RIE process with Digital Etch Technology for III-V Features of High Aspect Ratios

Led by	**Jesus del Alamo**	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	Lam Research	Fremont, CA

Developed for III-V nanowires, as part of Theme I's TFET research, the REI digital dry etch technology has found great use in other research programs in the del Alamo group. This technology has proven to be transformational. Excellent device results have demonstrated the potential of III-V MOSFETs for future CMOS. During period 9, **Jesus del Alamo** (*MIT*) has continued his joint work with Lam Research to assess and test the technology for broader applications.

Table 4.9. Characterization of 2D Materials

Led by	**Jing Kong**

Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	Applied Materials	Santa Clara, CA

The MIT work on 2D materials for TFET applications in the group of Prof. **Jing Kong** (*MIT*) has proven important for the Center's industrial partner, Applied Materials. Applied Materials has set up a research contract with the Kong group for helping them characterize and evaluate the 2D materials synthesized by the Applied Materials R&D team, with main focus on graphene and MoS2.

Table 4.10. Magnetoelectric Nanoparticles for Batteries

Led by	**Sakhrat Khizroev**	
Organizations Involved		
	Name	*Address*
1.	FIU	Miami, FL
2.	Turning Point Brands	Louisville, KY

Sakhrat Khizroev (*FIU*) has continued his spin-off work on primary and secondary battery cells based on magnetoelectric nanoparticles supported by an industry award from Turning Point Brands.

Table 4.11. Negative Capacitance Transistors

Led by	**Sayeef Salahuddin**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Intel Corp.	Hillsboro, OR
3.	TSMC	San Jose, CA (Headquarters: Taiwan)
4.	GlobalFoundries	Santa Clara, CA

Initially, negative capacitance transistor research was part of the Center for E^{3}S. However, since the anticipated overall device characteristics did not fit the main goals of the Center, this research was moved out of E^{3}S, and the new Berkeley Center for Negative Capacitance Transistors was formed with broad industry support from Intel, TSMC and GlobalFoundries, and **Sayeef Salahuddin** and **Chenming Hu** (both *Berkeley*) as co-directors.

- *Knowledge Transfer into the Center*

  The Center for E^{3}S regards knowledge transfer into the Center as important as knowledge transfer out of the Center. E^{3}S thus has continued to keep strong ties with industry and research labs, and transferring knowledge from these partners back into the Center. Knowledge transfer back into the Center is a fertile breeding ground for new ideas and enables Center researchers (faculty, postdocs and students) to learn from other leaders in related research and technology areas.

Table 4.12. Research Briefing with Industry Partners

Led by	**Eli Yablonovitch**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	UTEP	El Paso, TX
4.	Stanford	Palo Alto, CA
5.	FIU	Miami, FL
6.	Applied Materials	Santa Clara, CA
7.	HPE	Palo Alto, CA
8.	IBM	Yorktown Heights, NY
9.	Intel Corp.	Hillsboro, OR
10.	Lam Research	Fremont, CA

This year, representatives from all five companies comprising the E^{3}S Industrial Research Board (see table above) participated in the Center's Annual Retreat. During the retreat, our industry partners interacted with the Center leadership team, faculty, students, postdocs and staff and were updated on current projects and plans. In return, the Center received valuable feedback from all of the industry partners, in particular with respect to legacy building.

Table 4.13. Seminars by Invited Speaker

Led by	**Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	UC Santa Cruz	Santa Cruz, CA
2.	UC Riverside	Riverside, CA
3.	Strobe, Inc. (Cruise Automation)	Pasadena, CA
4.	Georgia Tech	Atlanta, GA
5.	Lam Research	Fremont, CA
6.	UC Berkeley	Berkeley, CA
7.	MIT	Cambridge, MA
8.	Stanford	Palo Alto, CA
9.	UTEP	El Paso, TX
10.	FIU	Miami, FL

In this period, in addition to seminars from Center members, we partnered with the Berkeley Solid State seminar series and co-sponsored selected talks from external speakers, including Prof. **Marco Rolandi** (*UC Santa Cruz*), Dr. **Lute Maleki** (*Strobe, Inc.*), Prof. **Muhannad Bakir** (*Georgia Tech*), and Prof. **Sandeep Kumar** (*UC Riverside*). In addition, the Center invited **Nerissa Draeger** from our industrial partner *Lam Research* to present a seminar to our summer undergraduate REU students. More details about seminars can be found at *https://e3s-center.berkeley.edu/news-events/seminars/*. All seminars broadcast to all Center members *via* Webex.

Table 4.14. Student Visit of Lam Research Facilities

Led by	**Lea Marlor**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Lam Research	Fremont, CA

This summer, we were fortunate again to be invited back by Lam Research for a visit by our graduate students and the summer REU student cohort. This year's visit of the Lam Research headquarters in Fremont, CA, was coordinated by E^3S diversity director (**Kedrick Perry**), education director (**Lea Marlor**), and **Nerissa Draeger** from Lam Research. The visit included a tour of the manufacturing units, including the impressive cleanroom facilities. Students also had the chance to speak to representatives of Lam Research.

- *Education Knowledge Transfer*

The Center for E^3S was again present at the most important national education and diversity events, and continued its fruitful interactions with the broader community. Doing so, education associate director **Lea Marlor** and diversity director **Kedrick Perry** engaged in knowledge transfer through written and oral dissemination of best practices, curriculum development and dissemination, and in-person outreach. In detail, E^3S participated in seven education, diversity and recruiting events, including the National Society of Black Engineers (NSBE) Conference, the Collaborative Network for Engineering and Computing Diversity (CoNECD) Conference by the American Society for Engineering Education (ASEE), the Society of Hispanic Professional Engineers (SHPE) Conference, the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) Conference, the Society of Women Engineers (SWE) Conference, and the Out in Science, Technology, Engineering and Math (OSTEM) Conference.

Table 4.15. Presentation at American Society for Engineering Education (ASEE)

Led by	**Lea Marlor**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	ASEE Conference, June 2018	Salt Lake City, UT

E^3S education associate director, **Lea Marlor**, presented a paper at the peer-reviewed American Society for Engineering Education Conference (ASEE) in June 2018 on "The Development of a Context-based Summer Research Program for Community College Faculty in Science and Engineering". This paper was co-authored with **Catherine Amelink**, external evaluator of the Center for E^3S.

2b. *Outcomes*

Outcomes of knowledge transfer activities of the Center for E^3S in this reporting period have been discussed in the previous section, as part of the description of each activity.

2c. *Table 4.16. Performance Against Metrics*

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Knowledge Transfer	Center publications	P2-5: 18 P6-7: 25 P8-P10: 30	21	21	27	46	39	37	31	39 (7 subm)
	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26	21
	Center sponsored symposia & workshops	P2: Baseline P3: 0 P4: 1 P5: 0 P6: 2 P7-9: 1 P10: 2	1	0	1	0	1	1	2	2
	External citations of publications *(cum)*	P3: 10 P4-5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase	6076 40% increase
	Industry contacts:									
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8	7
	Patent disclosures									
	• Disclosure/Provisional	P3: 3 P4: 3 P5: 5 P6: 2 P7: 2 P8: 3 P9-P10: 4	1	0	1	0	2	1	4	0

	• Patent/Patent Application	P4: 0 P5: 3 P6: 1 P7-P9: 2 P10: 3	1	2	1	3	8	4	1	2
	Technologies attributable to Center's research		(new for P6-10)				0	0	0	1
	• Low energy devices	P6-P9: 0 P10: 1								
	• Enabling other applications	P6-7: 0 P8-P9: 1 P10: 2								
	Center's alumni into relevant industries	P5: 50% P6-7: 30% P8-P9: 40% P10: 50%	Student 0%	Student 64% (7)	Student 16% (2)	Student 16% (6)	Student 50% (12)	Student 22% (2)	Student 33% (4)	Student 22% (2)
			Postdoc 100% (1)	Postdoc 33% (2)	Postdoc 20% (2)	Postdoc 40% (4)	Postdoc 13% (1)	Postdoc 18% (2)	Postdoc 60% (3)	Postdoc 0
	Center’s alumni pursuing research in academia & research labs in disciplines related to the Center	P6-10: 30%	(new for P6-10)				Student 38% (9)	Student 78% (7)	Student 58% (7)	Student 56% (5)
							Postdoc 88% (7)	Postdoc 82% (9)	Postdoc 40% (2)	Postdoc 83% (5)

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

2d. Knowledge Transfer Activities in Period 10

The Center for E^{3}S will further extend and strengthen its activities in creating an impactful and lasting legacy while continuing its current broad knowledge transfer program.

In particular, we will finalize and launch our *nanoHUB.org* website, make educational videos available to a wide audience from high school to graduate student level, and publish the first chapters of our open-access e-book on energy efficient electronics. We will also further strengthen knowledge transfer from our successful educational and diversity programs, in particular, our summer research experience programs for California community college students and faculty, by publishing journal articles and conference proceedings.

V. EXTERNAL PARTNERSHIPS

1a. *Goals and Objectives*

As an NSF Science and Technology Center, E^{3}S has regarded collaborations and partnerships an integral part of its structure and mission. Developing new partnerships and nurturing existing ones has been a major aim of the Center since its inception in 2010. In this regard, the multi-institutional structure of E^{3}S is ideally suited to extend its collaborative nature to external partners. E^{3}S has built external partnerships (formal and informal) with industry, national labs, policy makers, and educational institutions in various aspects of Center activities, from research, to education, knowledge transfer and broadening participation. As discussed in detail in the Knowledge Transfer section of this report, partnerships with industry are one of the cornerstones of the two-way knowledge transfer strategy of E^{3}S. The education and diversity programs leverage the experience, expertise and resources of campus partners at the lead and subaward institutions as well as off-campus partners to deliver highly successful programs. In period 9, the Center has continued to execute and enhance its partnership strategy to enable successful achievement of all its goals.

1b. *Performance Metrics*

Objective	Metrics	Frequency	Targets
Knowledge Transfer	Number of Contacts with Industry	Yearly	Period 2: 18 Periods 3-10: 36
	- Talks given to and meetings with industry		
	- Talks given by industry		Periods 2-10: 2
	Research Collaborations (started in period 6)	Yearly	Periods 6-7: 3 Periods 8-10: 4

The metrics for external partnerships, in part, co-align with the "knowledge transfer with industry" metrics. The rational for this lies in the fact that the Center for E^{3}S regards industry partnerships as critical to the success of practical implementation of its research outcomes. However, this—in no way—implies that E^{3}S does not consider external partnerships at all aspects of the Center's work critical to its success. Indeed, the Center has continued to engage external partners to accelerate its work towards the Center's goals. As in past reporting periods, the Center will continue to track the number of contacts with industry in two categories: i) talks given to and meetings with industry; ii) presentations to Center members by industry. The two metrics, in place since the start of the Center, measure the sharing of information. In period 6, the new metric, number of research collaborations, was added to measure depth of engagement with industry.

1c. *Problems Encountered*

Nothing to report.

2a. *Activities in Period 9*

The Center has continued to engage industry partners to accelerate research and knowledge transfer.

- Participation as a member in the E^{3}S Industrial Research Board has continued to be the primary route for companies to engage with the Center on a sustained basis; see Center Management section. The five member companies are Applied Materials, HP Enterprise, IBM, Intel Corporation, and Lam Research. Besides serving as advisors to provide the Center with industry perspectives, these companies support the Center's activities, including financial support in limited cases. In Period 9, three of the five member companies had additional engagement with the Center beyond an advisory level.

  - *Applied Materials*
    - **Jing Kong** (*MIT*) has formed a partnership with Applied Materials for characterizing and evaluating the 2D materials synthesized by the Applied Materials R&D team.
    - **Vladimir Stojanović** (*Berkeley*) is in discussion about a joint research project with Applied Materials and has presented a talk at Applied Material's 2018 Engineering and Technology (ET) Conference.
  - *Lam Research*
    - **Jesus del Alamo** (*MIT*) has a continued partnership with Lam Research to conduct laboratory evaluation of the high aspect ratio digital etch technology for broader semiconductor applications.
    - **Jeffrey Bokor** (*Berkeley*) had multiple contacts with Lam Research about joint projects and participated in the 2018 Lam Research Symposium.
  - *Intel Corporation*
    - Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) is an elected Board of Directors member at Intel Corporation.
  - In addition, **Jeffrey Bokor** and
- Other companies work with the Center in focused and limited manner.
  - **Jing Kong** (*MIT*) and **Philip Wong** (*Stanford*) had multiple visits and research discussions about joint projects with TSMC.
  - Former E^{3}S investigator **Philip Wong** (Stanford) is now a vice president at TSMC.
  - **David Zubia** (*UTEP*) presented a research seminar at Texas Instruments, Dallas, to discuss potential research projects for the Stritch project.
  - Turning Point Brands has awarded **Sakhrat Khizroev** (*FIU*) a monetary industry award to comparatively study primary and secondary battery cells based on magnetoelectric nanoparticles

In this period, the Center has continued its partnership with the Graduate Division of the UC Office of the President (UCOP) to fund a research internship program for undergraduates from Historically Black Colleges and Universities, the UCB-HBCU program. This program offers paid research experiences at UC Berkeley and at the HBCU home institution for a duration of 15 months. The program, which is managed by E^{3}S as an extension of the E^{3}S REU program, is partially funded by UCOP and the E^{3}S REU program.

The Center has continued to address the need for additional support to interns with backgrounds traditionally under-represented in STEM by partnering with the Berkeley Graduate Engineering and Science Students (BGESS). With funding from Berkeley's College of Engineering Student Services, BGESS, a networking event was again held in this period for all African-American REU interns who were hosted by E^{3}S managed programs, as well as interns from all summer research programs.

The Center partnered again with industry partner, Lam Research for a tour of its facilities in Fremont, CA, to the Center's summer students in conjunction with the Center's Education and Diversity efforts. A Lam Research representative, **Nerissa Draeger**, also came to Berkeley to present a seminar to E^{3}S students.

In period 9, the Center provided mentoring, advising, and sustained social and research support to four students from the Nanosystems ERC for Translational Applications of Nanoscale Multiferroic Systems (TANMS). TANMS is a multi-institutional ERC, based at UCLA, focusing on research, technology translation, and education associated with magnetism on the small scale. TANMS has faculty members at Berkeley who are also part of the Center for E^{3}S (**Jeffrey Bokor** and **Sayeef Salahuddin**). Thus, the four TANMS students at Berkeley were fuly integrated into the E^{3}S REU so they could take advantage of being a part of a dedicated cohort community, attend lectures, develop their science communication, and visit our industry partners. This integration led to TANMS students having high levels of satisfaction during the summer and developing positive outcomes pertaining to their research at Berkeley.

The above discussions of partnership activities are not intended to be inclusive of all partnerships that the Center relies on as it works towards its goals. A summary list of all partners are given in the Centerwide Output section of this report.

2b. Outcomes and Impact

The outcomes and impact are given above and in the Knowledge Transfer section.

2c. Performance Against Metrics

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Knowledge Transfer	Industry contacts:									
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8	7

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

2d. Partnerships Plans for Period 10

The recent breakthrough in the nanomechanics theme by demonstrating NEM relay-based integrated circuits operating at 50 mV (see Research section) are expected to be of interest to industry. Center management and the leadership team will assist researchers in deepening the engagement level with the existing industry members, as well as recruiting additional industry members, if necessary.

We expect that our existing research partnerships with key industry representatives will extend into period 10, while new ones will be formed as opportunities arise.

During summer 2019, all E^{3}S external education partnerships are expected to continue at the same level, to ensure the best experience for the summer students. In period 10, the Center will continue to seek strategic education and diversity partnerships with the goal of providing research experiences to under-representative minority populations, in particular women and racial minorities who are majoring in Electrical Engineering. In this regard, we will continue to host TTE students funded by the NIH Center for Genomics Editing and Recording (PI: Jennifer Doudna). Additionally, the Center is planning to expand its collaboration with the Tsinghua-Berkeley Shenzhen Institute (TBSI), which is co-directed by E^{3}S Faculty member, **Prof. Chang-Hasnain**, about possibly hosting students funded by TBSI.

VI. DIVERSITY

1a. Goals and Objectives

To enable the vision of contributing to a diverse STEM workforce, the Center for Energy Efficient Electronics Science strives to broaden participation by recruiting and retaining individuals from groups traditionally underrepresented in the disciplines represented in the Center. Moreover, we aim to foster their development and aid them in the transition to scholars, researchers, or members of the STEM workforce. In particular, the Center focuses on participation by those who may identify as underrepresented based on their racial/ethnic group, gender, LBGTQ status, veteran status, first-generation status, socioeconomic status, and difference in ability.

With the goal of broadening participation within E^{3}S disciplines of those with an underrepresented status among students, faculty, and the STEM workforce, the Center has implemented programs that allow individuals to be introduced and engaged in E^{3}S research. Furthermore, we cultivate an inclusive environment that embraces, and encourages intellectual curiosity and socio-cultural development.

The Center infuses equity and inclusion throughout its programmatic endeavors to enhance both the academic experience and the scholarly environment to prepare students to enter an increasingly complex and diverse society. Since the inception of the Center for E^{3}S, significant efforts to increase diversity were aimed at reaching students at the pre-college and college level. Engaging these students and increasing the diversity of STEM-based pre-college and college students in the Center has been a tool to increase diversity at the graduate and postdoc levels.

In period 9, the Center concentrated on further strengthening programs and initiatives to align with our goal of increasing diversity in the field of low-energy electronic devices and nurturing a diverse pool of participants in our pipeline. Additionally, the Center has continued to track past participants and provide advising, support, mentoring, and preparation for applying for transfer admission to a four-year institution or for graduate school.

Online Laboratory for High School Students: This period, the Center maintained high student engagement in E^{3}S topics by continuing to provide more hands-on activities. MOSTEC students were provided with breadboards, Raspberry Pi, and additional electrical components to complete their final projects. These hands-on activities, a best practice, are an effective way to increase engagement among all students including those from diverse background. In addition to new projects, students conducted Electrical Engineering and Computer Science (EECS)-themed lab assignments and projects and received college coaching and various workshops on E^{3}S topics.

Sustained Diversity Recruitment Initiatives: The Center has remained committed to the recruitment of graduate and undergraduate students from underrepresented groups into our programs. During this period, the Center has continued its partnership with Historically Black Colleges and Universities (HBCUs) to offer undergraduates students from HBCU institutions a summer research experience, and if eligible, a second summer experience in the E^{3}S REU program. The Center has seen success with the program as evidenced by the fact that an alumna of the program is now a second-year doctoral student in electrical engineering at Berkeley working on an E^{3}S project.

The HBCU summer research experience is funded by the University of California Office of the President (UCOP). This period the Center hosted three students from Jackson State University in Mississippi. It is expected that continuous engagement with students and faculty from HBCUs will enhance the students' experience and preparation for graduate study at UC Berkeley and other E^{3}S schools. The UCOP award also funds faculty development workshops, in which Berkeley and HBCU faculty come together to cultivate research collaborations, discuss research interests, identify research synergies, and share projects the undergraduate researcher can work on at UC Berkeley and the HBCU home institution.

In period 9, the Center aimed to increase diversity by participating in several recruiting events across the nation. This year, **Lea Marlor**, attended annual conferences of the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS), Society of Hispanic Professional Engineers (SHPE), the CUR Symposium, and the EEC Grantees Conference; and **Kedrick Perry** attended the Society of Women Engineers (SWE). E^{3}S also had representation at the American Indian Science and Engineering Society (AISES), Out in STEM (OSTEM) and plans to attend the National Society of Black Engineers (NSBE) conference in the spring. At each conference, information about E^{3}S topics, summer research experiences, and graduate programs were presented to a diverse group of students. Additionally, the Center has continued to incorporate topics related to inclusion and diversity awareness into the fabric of E^{3}S. During the annual retreat of Period 9, **Kedrick Perry** once again gave a talk incorporating concepts of diversity. This year's talk focused exclusively on gender issues.

1b. Table 6.1. Performance Metrics

Objective	Metrics	Frequency	Targets
Diversity	Women in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 20% Periods 6-9: 25%
	Underrepresented minorities in the Center's research programs	Annually	Period 2: baseline Period 3: 15% increase Period 4: 5% Period 5: 10% Period 6: 10% Period 7: 12% Period 8: 20% Period 9: 15%
	Participants from underrepresented* groups in the Center's Diversity programs	Annually	Period 3: Baseline Period 4: 80% Period 5-9: 85%
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center *(new)*	Annually beginning in Period 6	Period 6: 40% Period 7: 45% Period 8: 45% Period 9: 50%
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate *(new)*	Annually beginning in Period 6	Period 6-9: 85%
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering *(new)*	Annually beginning in Period 6	Period 6-9: 80%

1c. Problems Encountered

In period 9, the Center is still challenged by the lower than optimal number of women and underrepresented minorities at the graduate student level. The Center has remained diligent in its efforts to increase the number of these two groups; however, a significant increase has been slow. One reason for the slow progression is the difficulty of transitioning undergraduate students from the Center's research programs (i.e., REU and E^{3}S internship). While many former undergraduate students continue on to graduate school, they are not continuing their tenure on an E^{3}S project. However, they still pursue graduate research in a STEM field. Another issue on the horizon is funding. As the Center begins to wind down, we are in the process of looking for funding to continue our education and diversity programs.

2a. Development of US Human Resources

In period 9, the Center has ensured that its diversity programs include a strong integration with the Center's research activities. The Center continues to partner with nationally recognized pre-college and higher education programs and has formed alliances to collectively tackle the challenge of building a diverse pipeline of students who will enter and diversify the workforce. The Center has developed a clear understanding of which activities are effective for advancing underrepresented groups in high schools, community colleges, 4-year institutions, and graduate schools. The Center continues to conduct strategic planning meetings with representatives from diversity programs at Berkeley, UTEP and MIT, and program partners at Los Angeles Trade-Technical College, Mathematics Engineering Science Achievement (MESA), and Berkeley's Transfer Alliance Project (TAP) to discuss partnership opportunities.

- *Pre-college Programs*

  In period 9, the Center continued to partner with MIT's Office of Engineering Outreach Programs (OEOP) on programs for high school seniors. These existing MIT programs promote early interest in science and engineering careers to students from underrepresented groups. The Center's main role is to promote the career path of electrical engineering and related technical fields. We do this by supporting the offering of electronics training in the MOSTEC program. Previously in the Goals and Objectives section, we shared the history of our involvement with OEOP and this partnership has continued in period 8.

Table 6.2

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**Ebony Hearn** (MIT) and **Lea Marlor** (Berkeley)
Intended Audience	Rising 12th grade high school students
Approx. Number of Attendees (if appl.)	Total: TBD

As a founding member of the MIT Online Science, Technology, and Engineering Community (MOSTEC), the role of the Center for E^{3}S is to provide electronics education resources. Now in its eighth year, the MOSTEC program continues to promote student interest in various fields of engineering and science and to assist them with aspects of the college application process. MOSTEC students complete online coursework and projects in science, engineering, and technical writing. In July, MOSTEC students from all over the country gather for the MOSTEC Conference at MIT. Participants are exposed to MIT's faculty and staff who provide them with admissions and financial aid tips, lead electronics workshop, facilitate discussions about science and engineering research, and provide mentorship opportunities. After the conference, the students continue to learn more about science and engineering, interact with college faculty and staff, and receive online mentorship from undergraduates, graduate students, and industry professionals through the MOSTEC online platform.

Of our MOSTEC alumni (excluding the 2018 cohort), 56% (145) have gone on to major in a STEM degree. Of these students, 97 (67%) are underrepresented with 54% (79) underrepresented minorities and 30% (43) female.

- *Undergraduate Programs*

  At the undergraduate level, the Center's programs target two different audiences - community college students and students at 4-year universities. The Center aims to provide a bridge experience for community college students to help promote their transfer to a 4-year baccalaureate institution. For undergraduates at 4-year institutions, research is used as an early engagement vehicle to attract the students to the Center's focus on low-energy electronic devices.

  Community College Programs: The Transfer-to-Excellence (TTE) program, founded by the Center at its inception, is a residential summer research program (TTE REU) that brings community college students to Berkeley to undertake a research project hosted by a Berkeley faculty.

  While at Berkeley, TTE participants earn a stipend and have access to enrichment activities to build resilience in the pursuit of a STEM education and career. For the academic year following the completion of one component, each participant continues to receive advising and support in his/her efforts to transfer to a STEM baccalaureate program from Berkeley's Transfer Alliance Project (TAP).

Table 6.3

Activity Name	Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU)
Led by	**Lea Marlor** (Berkeley) and **Jeff Bokor** (Berkeley)
Intended Audience	Community college students
Approx. Number of Attendees (if appl.)	Total: 6 Females: 2 (33%), URMs: 1 (17%), First Gen: 4 (66%)

During summer 2018 (Period 9), E^3S at UC Berkeley hosted six of fifteen community college students in the TTE REU program (TTE REU Recruitment Flyer: https://e3s-center.berkeley.edu/wp-content/uploads/2018/11/2019-Flyer.pdf These students completed nine weeks of research in the laboratories of E^3S faculty, **Ming Wu**, and **Jeff Bokor**; and E^3S Education Affiliates, **Laura Waller** and **Alex Zettl**. Education Affiliates are not part of the Center's research team, but their research disciplines are similar to those of the Center.

In Period 9, the TTE REU experience started with a one-week bootcamp on the fundamentals of electronics, laboratory procedures, safety training, ethics training, and software training before embarking on independent research. During the 9 weeks of hands-on independent research, the TTE REU students also attended a variety of enrichment activities and participated in weekly one-on-one mentorship meetings with **Lea Marlor.** For details on enrichment activities, see https://e3s-center.berkeley.edu/wp-content/uploads/2018/11/Draft-Calendar-for-website.docx

TTE participants were trained on scientific ethics, technical presentations, and science communication, received individualized academic and transfer advising, and participated in group enrichment activities provided by TAP. At the end of the program, the students write a brief research paper, and present their research at a poster session and a research symposium.

To date, 94% (34) of the Center's TTE alumni who were eligible to apply for transfer admission to a 4-year institution have either transferred to a baccalaureate program majoring in STEM or graduated with a bachelor's degree in STEM. Of the students who have transferred, 91% (31) enrolled at a UC campus; 74% (25) enrolled at UC Berkeley, and 90% (38) were from underrepresented groups. The Center is actively conducting research to determine the impact of TTE on transfer rates, self-efficacy, and graduate school matriculation rates. This project is led by **Lea Marlor**.

Summer Research Programs for Undergraduate Students from 4-Year Institutions: The Center hosts a Summer REU program at all E^{3}S affiliated schools, and this period it was hosted by Berkeley, UTEP, and MIT. The primary goal is to attract undergraduate students, particularly those from groups underrepresented in science and engineering, to the Center's research in energy efficient electronics science, and graduate studies in science and engineering at the Center's member institutions.

Table 6.4

Activity Name	E^{3}S Research Experiences for Undergraduates at Berkeley & MIT (E^{3}S REU)
Led by	**Kedrick Perry** (Berkeley) and **Eli Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx. Number of Attendees (if appl.)	Total: 12 Female: 6 (50%), URMs: 6 (50%)

The Center's 9-week E^{3}S REU program received 84 applications. Ten of these students were matched with Center faculty at Berkeley, one at UTEP, and two were matched at MIT. At MIT, our student were hosted by **Jesus del Alamo**. At Berkeley, students were hosted by E^{3}S faculty, **Tsu-Jae King Liu**, **Jeff Bokor**, **Eli Yablonovitch**, **Ming Wu, , Felix Fischer**, **Junqiao Wu**, **Sayeef Salahuddin** and **Vivek Subramanaian** (affiliate). In addition to research activities, students attended weekly enrichment activities that included field trips and preparation for the GRE. This summer, LAM Research provided the students an overview of LAM's research technology, labs and a tour. Each student also received one-on-one mentorship meetings with **Kedrick Perry**, the Center's Director of Diversity. For calendar of events and activities, see: https://e3s-center.berkeley.edu/wp-content/uploads/2018/10/REU-2018-Calendar-v4.pdf

At the end of the summer research program, the students completed a short research paper, a 15-minute research presentation, and a poster. The poster was presented at a joint poster session that featured posters from several REU programs.

Recruitment and Public Outreach

In addition to these diversity programs, Center members attend diversity conferences and give seminars to local pre-college, undergraduate and graduate audiences to share the exciting work of the Center and present student involvement opportunities. Often, these seminars target underrepresented groups, including individuals from underrepresented racial/ethnic backgrounds, women, and students from low socioeconomic backgrounds. In Period 9, the Center targeted students at institutions that may not offer, or have limited offerings in, courses and research on energy efficient electronics science.

This fall, E^{3}S collaborated with UC Berkeley's College of Engineering to recruit for the Center's diversity programs, targeting students at 4-year institution and community colleges.

For the community college programs, **Lea Marlor** visited four 2-year colleges with plans to visit more in January. Additionally, six online information sessions were hosted for students from community colleges that Ms. **Marlor** was unable to visit. These activities were typically one-hour presentations on the research opportunities available to community college students and on how to successfully apply to the program and for transfer. The Center also supported several students from its summer TTE research program to present their research in a poster session at the Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Conference.

2b. Impact on the Center's Diversity

In period 9, the Center has committed available resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. We believe active recruitment ensures that E^{3}S programs will have access to competitive candidates and highly qualified participants, regardless of race, color, or gender. As a result, we are beginning to see more students from underrepresented groups pursue research in the Center or closely related science and engineering fields.

The Center has been able to successfully develop a talent pool of students at the pre-college and undergraduate level. These students have been exposed to energy efficient electronics science through research or lecture. To date, approximately over half of our participants in the diversity programs come from underrepresented groups, including women and underrepresented minorities. Among the students who participated in our pre-college programs, over half are pursuing a bachelor's degree in science and engineering.

In summary, the Center has continued to make diversity a high priority in Period 9. The Center leveraged existing partnerships with nationally recognized pre-college and higher education programs and has formed new alliances to collectively tackle the challenge of building a diverse pipeline of students who will eventually contribute to a diverse workforce.

2c. Table 6.5. Performance Against Metrics

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Diversity	Women in the Center's research programs	P2: Baseline P3: 5% P4: 30% P5: 20% P6-10: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)	12 (14%)	20 (23%)
	Underrepresented minorities in the Center's research programs	P2: baseline P3: 15% P4: 5% P5-6: 10% P7-8: 12% P9-10: 15%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)	11 (13%)	15 (17%)
	Participants from underrepresented* groups in the Center's Diversity programs	P3: Baseline P4: 80% P5: 85% P6: 85% P7: 85% P8-P10: 85%	n/a	n/a	Women 37 (44%)	Women 26 (41%)	Women 29 (40%)	Women 25 (40%)	Women 38 (44%)	Women 40 (42%)
					URMs 58 (68%)	URMs 36 (56%)	URMs 49 (67%)	URMs 38 (60%)	URMs 48 (55%)	URMs 50 (58%)
				Total 93 (82%)	Total 73 (86%)	Total 49 (77%)	Total 66 (90%)	Total 63 (87%)	Total 69 (80%)	Total 68 (77%)

	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center	P6: 40% P7: 45% P8-P10: 50%	(new for P6-10)	17 (55%)	23 (54%)	27 (50%)	30 (55%)
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate	P6: 85% P7: 85% P8-P10: 85%	(new for P6-10)	16 (70%)	22 (81%)	24 (80%)	30 (88%)
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering	P6: 80% P7: 80% P8-P10: 80%	(new for P6-10)	73 (55%)	102 (63%)	14 (33%)	TBD

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

2d. *Plans in Period 10*

In period 9, the Center will continue to be staffed by Associate Director for Education, **Lea Marlor**, and Diversity Director, **Kedrick Perry**. E^{3}S will focus on maintaining and strengthening its to efforts to attract women and underrepresented minorities but also seek to gain greater traction in attracting first-generation students, low-income students, those of varying ability/disability statuses, and veterans. **Perry** will continue efforts to draw students from HBCUs through the activities of the UCB-HBCU program. **Perry** will also continue to seek out funding to continue the diversity and education programs.

In period 9, greater emphasis was placed on selecting electrical and electronics engineering undergraduates to ensure that when they joined a Center member institution, the students would be in a department with a choice of Center faculty to choose from as their advisors. This practice will continue in period 10 along with the use of national databases to target prime candidates, enhancing the profile of E^{3}S amongst diverse undergraduates, strengthening partnerships with minority-serving institutions, and building collaborations with organizations that focus on sending diverse students to graduate school such as the LSAMP program.

VII. MANAGEMENT

1a. Organizational Structure and Underlying Rationale

The organizational structure of the Center for E^{3}S is given in Appendix B. The most notable changes are (1) the departure of Prof. **H.-S. Philip Wong** (*Stanford*) from the Center and the Executive Committee, (2) the addition of Prof. **Shan Xiang Wang** (*Stanford*) to replace Prof. Wong as investigator in the Nanomagnetics research theme, and (3) the proposed addition of Prof. **Jeehwan Kim** (*MIT*) as investigator in the Nanophotonics research theme. The organizational structure and changes from the last report are discussed in the following in more detail.

- Executive Committee:
  a) As stated in the by-laws, the Center for E^{3}S leadership team is represented by the Executive Committee, consisting of

     i) Ex-officio members:
        - Eli Yablonovitch - Principal Investigator and Center Director
        - Jeffrey Bokor – Deputy Center Director, Theme Leader and Faculty Director for Diversity
        - Michael Bartl – Executive Director
        - Vladimir Bulovic – Site Head, MIT (the largest subaward institution)
        - Tsu-Jae King Liu – Theme Leader and Faculty Director for Education
        - Ming C. Wu – Theme Leader
        - Lea Marlor – Associate Director of Education
        - Kedrick Perry – Director of Diversity and Outreach

     ii) Elected members:
        - H.-S. Philip Wong, Stanford*
        - David Zubia, University of Texas at El Paso (UTEP)

        **H.-S. Philip Wong left the Center for E^{3}S effective July 1, 2018.*

  b) The new nine-member executive board (without H.-S. Philip Wong) was ratified at the July 2, 2018, Executive Committee meeting with 100% of the votes in favor.
  c) The by-laws of the E^{3}S Executive Committee were reviewed by the Center's leadership team. No changes were recommended and the by-laws were ratified at the July 2, 2018, executive committee meeting with 100% of the votes in favor.
- E^{3}S Management and Operations Team:
  - E^{3}S continues to be led and managed by executive director, **Michael Bartl**. The executive director oversees the Center administration, all programmatic aspects, the Center budget, the operation of the Center, and the management of the Center's staff team, consisting of the director of diversity and outreach, the associate director of education, the program coordinator, and various student assistants.
  - The Center's programmatic efforts in education and diversity are the responsibility of the associate director of education and the director of diversity and outreach. As has been the case since the start of the Center, the education and diversity programs enjoy faculty support through the two faculty director positions, which are currently held by **Jeffery Bokor** (faculty director for diversity) and **Tsu-Jae King Liu** (faculty director for education).

1b. *Table 7.1. Performance Metrics*

Objective	Metrics	Frequency	Targets
Center Management	Centerwide Communications *(discontinued)*	▨	▨
	Annual Surveys:		
	• Students /Postdocs	Annually	According to Likert scale: Periods 2-5: 3 or higher Periods 6-9: 4 or higher
	• Co-PIs	Annually beginning in Period 3	
	• External Advisory Board	Annually	
	Authorship disputes	Annually beginning in Period 3	Periods 2-5: 20% decrease Periods 6-9: 0
	Plagiarism	Annually	Periods 2-9: 0
	Changes in Center processes made in response to evaluation results *(new)*	Annually beginning in Period 6	- 3 months for closure of regular action items - 1 week for closure of time-sensitive action items
	Assessment of goals, objectives, and outcomes – Strategic Plan Review	▨	▨

1c. *Performance Against Metrics*

An important management aspect of the Center is to periodically seek feedback from faculty, students and postdocs in an effort to evaluate and maximize the effectiveness and performance of the leadership team with respect to the Center's core values:

- Inclusiveness
- Teamwork
- Open and Timely Communications
- Agility
- Focus on Performance
- Ethical Conduct

Since the very early stages of the Center this feedback is obtained through annual surveys, which are conducted, administered and analyzed by our external evaluator, **Dr. Catherine Amelink**. Dr. Amelink then reports the result of the surveys (with all names and personal information removed) to the E^{3}S leadership team.

Table 7.2. Center Management Metrics Table

Category	Metric	Targets	Results							
			P2	P3	P4	P5	P6	P7	P8	P9
Center Management	Annual Surveys:	Measured and reported on Likert Scale								
	• Students /Postdocs	P2-5: 3 or higher P6-10: 4 or higher	Average 3.9±0.2	Average 4.0±0.3	Average 4.2±0.2	Average 4.5±0.2	Average 4.3±0.2	Average 4.3±0.3	Average 4.4±0.1	Average 4.3±0.2
	• Co-PIs		No survey	Leadership 4.46	Leadership 4.7±0.5	Leadership 4.9±0.1	Leadership 4.6±0.1	Leadership 4.8±0.2	Leadership 4.8±0.1	Leadership 4.8±0.1
	• External Advisory Board		Strategic Plan: 4.2 Center Status 4.0	Strategic Plan: 4.1 Center Status 4.0	Strategic Plan: 4.6 Center Status 4.6	Strategic Plan: 4.4 Center Status 4.7	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	N/A
	Authorship disputes	P2-5: 20% decrease P6-10: 0	0	0	0	0	0	0	0	0
	Plagiarism	P2-10: 0	0	0	0	0	0	0	0	0
	Changes in Center processes made in response to evaluation results	3 months for closure of regular action; 1 week for closure of time-sensitive action	(new for P6-10)				0	0	0	0

Legend: *P2, P3, P4, P5, P6, P7, P8, P9, P10 refers to Period 2, Period 3, Period 4, Period 5, Period 6, Period 7, Period 8, Period 9, Period 10, respectively.*

Two center-wide perception surveys are conducted annually: 1) Postdocs and graduate student survey (see also Appendix L) and 2) faculty survey (see also Appendix M). Period 9 has been the eight year in which the graduate students & postdocs survey has been conducted. The faculty and the postdoc/student surveys resulted in overall average leadership ratings of 4.8 and 4.3 on the Likert scale (Likert scale points definition: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree), indicating a very positive evaluation of the Center leadership team and the Center structure by all members.

As discussed in previous reports, the survey question "Since joining the Center I have developed a working relationship with someone in the Center who is not part of my home institution" consistently has a lower score on the Likert scale. This year the score was 3.6 with a standard deviation of 1.4. Similarly, this year, the question "The Leadership Team is recognizing and evaluating me on my performance" received a score of 3.6 with a standard deviation of 1.3. Two things are interesting to note: 1) While these score are lower than all others, these are still positive scores on the Likert scale (between "Agree" and "Neutral"). 2) The large standard deviations indicate that students are divided on these question. The Center management and leadership takes these result very seriously. The first is a call to better inform all students and postdocs about the multi-institutional research and education opportunities in the Center, including the E^{3}S Graduate Student and Postdoc Rotation program. This program enables students and postdocs to spend several months at an E^{3}S partner institution to perform research or use facilities not available at their own institution. The second survey result might be a reflection that the Center experimented to some extent with the seminar program. To increase seminar interest, we focused more on outside speakers this year, whereas in previous years Center students and postdocs had more opportunities to present their work at seminars. In response to the survey result, we will revert back to our previous seminar structure and give our students and postdocs speaking priority.

Below is a mean-scores period-to-period comparison with respect to the Center's core values:

	P2	P3	P4	P5	P6	P7	P8	**P9**
Inclusiveness	3.8	4.1	4.1	4.6	4.4	4.3	4.5	**4.5**
Teamwork	3.7	3.6	4.0	4.6	4.2	4.2	4.3	**4.3**
Open and timely communications	4.0	4.2	4.2	4.7	4.2	4.4	4.5	**4.4**
Agility/Decision Making	4.0	4.1	4.2	4.5	4.4	4.4	4.4	**4.3**
Focus on Performance	3.8	4.1	4.1	4.5	4.2	4.2	4.2	**4.2**

While year-to-year differences are likely to be within the range of data uncertainties, when comparing the data over time, the Center's graduate students and postdocs continue to recognize the efforts of the Center leadership in creating a positive climate in a favorable way.

As in past years, the externally administered anonymous survey also asked for incidents that can be considered to be unethical conduct. Again, continuing the previous trend, no unethical incidents were reported. The faculty survey had the same outcome: All faculty respondents answered the question "*I feel that my E^{3}S colleagues act in an ethical manner*" with YES.

1d. *Problems Encountered*

Due to scheduling difficulties, the planned meeting of the Center's Education Working Group (with selected members of the E^{3}S External Advisory Board) was combined with the External Advisory Board meeting on October 17, 2018. The Center's education and diversity leadership team discussed current education, diversity and outreach efforts with the working group members, and obtained valuable feedback.

2. *Management and Communications Systems*

Management: The E^{3}S Executive Committee continued to hold regularly scheduled meetings throughout the funding period to discuss the direction of the Center and make important decisions. All meetings are held by Webex to allow remote participation of members from different institutions. This period, so far, the Executive Committee has met four times with the fifth and final meeting being scheduled for December 18 (see details below).

At the September 21 Executive Committee meeting, the Center leadership team started in-depth planning efforts of how to minimize the impact of the scheduled budget reduction (overall 33 percent reduction) in the last 18 months of the Center (March 2019 through September 2020). Executive director, **Michael Bartl**, was tasked with developing a plan/budget to minimize the administrative impact and to ensure the Center stays fully operational. In addition, the Executive Committee decided to consider research budget cuts in its annual review of proposed Center-internal research programs for funding period 10. While all funding decisions for period 10 programs were made based on the quality, impact and potential for Center legacy of proposed projects, the committee was sensitive to potential impact on graduate students and postdocs. Final discussions were made at the November 2 Executive Committee meeting. The review and voting process ended with unanimous agreement on all the proposed programs as reported in this Annual Report.

Table 7.3. Executive Committee Meetings – Period 9

Meeting Dates	Agenda Topics
April 11, 2018	Review of Period 8 Spending; Vote on Period 9 Budget; External Advisory Board Membership Review; STC Site Visit Planning
July 2, 2018	Review and Ratification of By-Laws; Approval of Executive Board; Approval of External Advisory Board Membership; Annual Retreat Planning
September 21, 2018	Annual Retreat Debrief; External Advisory Board Meeting Planning; Implementation of Budget Reductions for Periods 10 and 11; Proposal Review Planning
November 2, 2018	Center-wide Annual Proposal Review; Site Visit Agenda Discussion
December 18, 2018	Review of the Center's Results vs. the Strategic Plan; Review of Preliminary Feedback from External Advisory Board; Site Visit Planning; Center Legacy

Communications and Planning: Traditionally, the foremost gathering and planning event for all Center faculty, students, postdocs and staff is the center-wide annual retreat. This year, the retreat was held on the UC Berkeley campus on September 20 and 21. During the retreat, all research, education and diversity programs as well as Center management and knowledge transfer activities were reviewed with respect to progress towards the main Center goals and legacy building. The retreat included research presentations from faculty, students and postdocs, representing all E^{3}S themes and system integration. These presentations are held on the first day of the retreat (see also retreat agenda, given as Appendix J), which was also attended by representatives from all five of our industry partners: **Namsung Kim** (Applied Materials), **Paul Solomon** (IBM), **Uygar Avci** (Intel), **Stanley Williams** (HPE, ret.), and **Nerissa Draeger** (Lam Research). The second day featured presentations about education and diversity achievements and plans, reports by the executive director on Center management and center-wide output, and a diversity training/workshop on "Enhancing Equitable Environments" by E^{3}S diversity director, **Kedrick Perry**. A significant portion of the second day was focused on E^{3}S legacy: *A Look Beyond 2020: Center Legacy* featured breakout groups for research and education as well as a lively all-Center discussion on how to best use the last 24 months of the Center to establish a lasting legacy in energy-efficient electronics.

The conclusions reached at the annual retreat and accompanying changes in the Center's research, education, diversity and management strategies are articulated in this annual report.

Our main communication tool throughout the year is the E^{3}S website: https://e3s-center.berkeley.edu/. This site, which was redesigned in the previous period, keeps Center members, affiliates, prospective students and postdocs, as well as the general public informed about Center activities and programs, key outcomes, and general stories related to energy-efficient electronics.

3. *Internal and External Advisory Bodies*

The Center for E^{3}S has two main advisory bodies, an *External Advisory Board* and an *Industrial Research Board.*

a. External Advisory Board: Members of the External Advisory Board have arms-length relationships with the Center and represent academia, national labs, and industry. All members and the chair of the External Advisory Board are appointed by the E^{3}S Executive Committee for limited terms:

- Chair: 2-year appointment term
- Members: 3-year appointment term
- Chair and member appointments are renewable, at the discretion of the E^3S Executive Committee, for additional 2-year appointment terms.

Limited-term membership was implemented at the beginning of the Center both to lessen the concern that an engagement as an E^3S external advisor can be onerous and to allow the Center to periodically refresh the composition of the External Advisory Board and adjust to changes in the Center's research, education and diversity strategies.

Changes from last funding period: 1) **Katherine Guzman** (*Sandia National Lab*) completed her five-year term with the ending of period 8. Dr. Guzman requested her term not to be renewed due to additional commitments at Sandia. She was thanked for her excellent service to the Center and was excused from the External Advisory Board. 2) The appointment term of **Paolo Gargini** (*IRDS*) as chair of the E^3S External Advisory Board was renewed for an additional 2-year term period. Dr. Gargini accepted the renewal of his term.

Led by chair Paolo Gargini, the current E^3S External Advisory Board members are:

Table 7.4. Center for E^3S External Advisory Board

Member	Affiliation
Samuel Bader	Argonne National Lab
Eun-Woo Chang	Ashland University
Paolo Gargini, *Chair*	International Roadmap for Devices and Systems (IRDS)
Elsa Garmire	Dartmouth College
Jonathan Heritage	University of California, Davis
Diane Rover	Iowa State University
Thomas Theis	Columbia University, ret.

A subset of external advisors functions as the Education Working Group to advise and guide the Center's education and diversity programs. It is important to note that the Education Working Group, chaired by **Diane Rover** (*Iowa State University*), does not assess the education and diversity programs—this is done as part of the annual evaluation by the entire External Advisory Board.

This year's annual meeting of the E^3S External Advisory Board was held at the UC Berkeley campus on October 17 (the agenda is given in Appendix C). The main purpose of these annual meetings is to update the External Advisory Board on the Center's progress in research, education, diversity, knowledge transfer, and center management, and to receive feedback and input from the members of this important advisory body.

All seven current members of the External Advisory Board participated in this year's meeting in person. Following the presentations by E^3S faculty, postdocs, students, and staff, the External Advisory Board members deliberated and started working on their written report to the Center. The meeting concluded with an oral feedback by all members, providing supportive comments, particularly with respect to the research progress and the student and postdoc speakers and poster presenters. The External Advisory Board was supportive of the legacy plans presented at the meeting and encouraged the leadership team to further increase efforts in this direction by planning aggressively beyond the duration of the Center and seeking strategic partners. A written report will be provided by Chair **Paolo Gargini**, who will also present the External Advisory Board's findings and recommendations at the upcoming NSF Site Visit.

b. Industrial Research Board: The Industrial Research Board is an important advisory body of the Center and we are appreciative of this continued support and close relationship with leaders in the semiconductor industry. The current members of the Center for E^{3}S Industrial Research Board are:

Company	**Main Contact**
Lam Research	Nerissa Draeger
IBM	Paul Solomon
Hewlett-Packard	Stanley Williams
Applied Materials	Ellie Yeh
Intel	Ian Young

As an integral part of our Center, the Industrial Research Board monitors, advises and participates in the Center's research. Interactions with the Industrial Research Board happens at several levels, including (1) visits and presentations by E^{3}S investigators, (2) participation of board members at the E^{3}S Annual Retreat and the biennial Berkeley Symposium on Energy Efficient Electronic Systems, (3) presentations by board members to our students, postdocs and faculty, and (4) hosting of E^{3}S students and postdocs.

The industry partners in attendance at this year's Annual Retreat were:

- Namsung Kim, Applied Materials
- Paul Solomon, IBM
- Uygar Avci, Intel
- Stanley Williams, HPE, ret.
- Nerissa Draeger, Lam Research

All industry partners in attendance participated actively in discussions and analyses of research results. In addition, Industrial Research Board members provided detailed feedback and comments to the E^{3}S leadership team in a closed session at the Annual Retreat (see also retreat agenda, given as Appendix J).

4. Changes in the Strategic Plan

No changes have been made to the Center for E^{3}S Strategic Plan (2015-2020) that was submitted to NSF in July 2014. All metrics reported and referred to in this annual report are part of the 2015-2020 Strategic Plan.

VIII. CENTERWIDE OUTPUT

1a. Publications

1ai. Peer Reviewed

Journal Articles Published *(chronological)*

1. T. Stewart, A. Nagesetti, R. Guduru, E. Stimphil, A. Hadjikhani, L. Salgueiro, P. Liang, J. Horstmyer, A. Schally, and **S. Khizroev**, “Magnetoelectric nanoparticles to deliver and release anti-tumor peptide into glioblastoma cells across blood-brain barrier via external application of d.c. and a.c. magnetic fields,” *Nanomedicine (London)*, vol. 13, pp. 423-438, Feb 2018.
2. B. Osoba, B. Saha, S. F. Almeida, J. Patil, L. E. Brandt, M. E. D. Roots, E. Acosta, **J. Wu** and **T.-J. K. Liu**, “Variability study for low-voltage micro-electro-mechanical relay operation,” *IEEE Transactions on Electron Devices*, Vol. 65, No. 4, pp. 1529 - 1534, Feb 2018.
3. Y. Chen, S. Huang, X. Ji, K. Adepalli , K. Yin, X. Ling, X. Wang , J. Xue, M. Dresselhaus, **J. Kong** and B. Yildiz, “Tuning Electronic Structure of Single Layer MoS2 through Defect and Interface Engineering”, *ACS Nano*, vol. 12, pp. 2569–2579, Feb 2018.
4. J. Hong, M. Stone, B. Navarette, K. Luongo, Z. Yuan, K. Xia, N. Xu, **J. Bokor**, L. You and **S. Khizroev**, “3D multilevel spin transfer toque devices,” *Appl. Phys. Lett.*, vol. 112, pp. 112402, Mar 2018.
5. R. Lo Conte, Z. Xiao, C. Chen, C. V. Stan, J. Gorchon, A. El-Ghazaly, M. E. Nowakowski, H. Sohn, A. Pattabi, A. Scholl, N. Tamura, A. Sepulveda, G. P. Carman, R. N. Candler and **J. Bokor**, “Influence of Nonuniform Micron-Scale Strain Distributions on the Electrical Reorientation of Magnetic Microstructures in a Composite Multiferroic Heterostructure,” *Nano Lett.*, vol. 18, pp. 1952-1961, Mar 2018.
6. X. Zhao, A. Vardi and **J. A. del Alamo**, “Excess Off-State Current In InGaAs FinFETs.” *IEEE Electron Device Letters*, Vol. 39, No. 4, pp. 476-479, Apr 2018.
7. B. V. Senkovskiy, D. U. Usachov, A. V. Fedorov, D. Haberer, N. Ehlen, **F. R. Fischer** and A. Grüneis, “Finding the Hidden Valence Band of N = 7 Armchair Graphene Nanoribbons with Angle-Resolved Photoemission Spectroscopy,” *2D Mater.*, vol. *5*, pp. 035007, Apr 2018.
8. K. Dong, H. S. Choe, X. Wang, H. Liu, B. Saha, C. Ko, Y. Deng, K. Tom, S. Lou, Z. You, J. Yao and **J. Wu**, “0.2-Volt microelectromechanical switch enabled by a phase transition,” *Small*, vol. 14, pp. 1703621, Apr 2018.
9. Z. Pedramrazi, C. Chen, F. Zhao, T. Cao, G. Nguyen, A. Omrani, H.-Z. Tsai, R. Cloke, T. Marangoni, D. Rizzo, T. Joshi, C. Bronner, W. Choi, **F. R. Fischer**, **S. G. Louie** and M. F. Crommie, “Concentration Dependence of Dopant Electronic Structure in Bottom-Up Graphene Nanoribbons,” *Nano Lett.*, vol. 18, pp. 3550-3556, May 2018.
10. Y. Gao, A. J. Goodman, P.-C. Shen, **J. Kong** and W. A. Tisdale, “Phase-Modulated Degenerate Parametric Amplification Microscopy,” *Nano Lett.*, vol. 18, pp. 5001-5006, Jun 2018.
11. B. V. Senkovskiy, D. Y. Usachov, A. V. Fedorov, T. Marangoni, D. Haberer, C. Tresca, G. Profeta, V. Caciuc, S. Tsukamoto, N. Atodiresei, N. Ehlen, C. Chen, J. Avila, M. C. Asensio, A. Varykhalov, A. Nefedov, C. Wöll, T. K. Kim, M. Hoesch, **F. R. Fischer** and A. Grüneis, “Boron-Doped Graphene Nanoribbons: Electronic Structure and Raman Fingerprint,” *ACS Nano*, vol. 12, pp. 7571–7582, Jul 2018.
12. K. Yin, S. Huang, X. Chen, X. Wang, **J. Kong**, Y. Chen, J. Xue “Generating Sub-nanometer Pores in Single-Layer MoS2 by Heavy-Ion Bombardment for Gas Separation: A Theoretical Perspective,” *ACS Appl. Mater. Interfaces*, vol. 10, pp. 28909-28917, Jul 2018.
13. M. S. Eggleston, S. B. Desai, K. Messer, S. A. Fortuna, S. Madhvapathy, J. Xiao, X. Zhang, **E. Yablonovitch**, **A. Javey** and **M. C. Wu**, “Ultrafast Spontaneous Emission from a Slot-Antenna Coupled WSe2 Monolayer,” *ACS Photonics*, vol. 5, no. 7, pp. 2701–2705, Jul 2018.

14. D. J. Rizzo, G. Veber, T. Cao, C. Bronner, T. Chen, F. Zhao, H. Rodriguez, **S. G. Louie**, M. F. Crommie and **F. R. Fischer**, “Topological band engineering of graphene nanoribbons,” *Nature*, vol. 560, pp. 204-208, Aug 2018.
15. R. Guduru, P. Liang, M. Yousef, J. Horstmyer, and **S. Khizroev**, “Electric field mapping of the brain with magnetoelectric nanoparticles,” *Bioelectr. Med.*, vol. 4, pp.10, Aug 2018.
16. J. Hong, K. Dong, **J. Bokor**, and L. You, “Self-assembled single-digit nanometer memory cells,” *Appl. Phys. Lett.*, vol. 113, p. 062404, Aug 2018.
17. Z. Gao, Q. Ji, P.-C. Shen, Y. Han, W. S. Leong, N. Mao, L. Zhou, C. Su, J. Niu, X. Ji, M. M. Goulamaly, D. A. Muller, Y. Li and **J. Kong**, “In-situ Generated Volatile Precursor for CVD Growth of a Semimetallic 2D Dichalcogenide,” *ACS Appl. Mater. Interfaces*, vol. 10, pp. 34401–34408, Sep 2018.
18. W. S. Leong, Q. Ji, N. Mao, Y. Han, H. Wang, A. J. Goodman, C. Su, Y. Guo, P.-C. Shen, Z. Gao, D. A. Muller, W. A. Tisdale and **J. Kong**, “Synthetic Lateral Metal-Semiconductor Heterostructures of Transition Metal Disulfides,” *J. Am. Chem. Soc.*, vol. 140, pp. 12354–12358, Sep 2018.
19. X. Zhao, C. Heidelberger, **E. A. Fitzgerald**, W. Lu, A. Vardi and **J. A. del Alamo**, “Sub-10-nm-Diameter InGaAs Vertical Nanowire MOSFETs: Ni Versus Mo Contacts,” *IEEE Transactions in Electron Devices*, vol. 65, pp. 3762-3768, Sep 2018.
20. N. Sato, F. Xue, R. M. White, C. Bi and **S. X. Wang**, “Two-terminal spin–orbit torque magnetoresistive random access memory,” *Nature Electronics*, vol. 1, pp. 508–511, Sep 2018.
21. Y. -L. Lee, F. Zhao, T. Cao, J. Ihm and **S. G. Louie**, “Topological phases in cove-edged and chevron graphene nanoribbons: Geometric structures, Z2 invariants, and junction states,” *Nano Lett.*, vol. 18, pp. 7247-7253, Sep 2018.
22. **S. Khizroev**, “Technobiology’s Enabler: The Magnetoelectric Nanoparticle,” *Cold Spring Harb. Perspect. Med.*, doi: 10.1101/cshperspect.a034207, published online, Oct 2018.
23. P.-C. Shen, Y. Lin, H. Wang, J.-H. Park, W. S. Leong, A.-Y. Lu, T. Palacios and **J. Kong**, “CVD Technology for 2D Materials,” *IEEE Transaction on Electronic Devices*, vol. 65, pp. 4040-4052, Oct 2018.

Under Review/Submitted *(alphabetical by 1st author)*

1. J. Lin, X. Zhao, I. Manglano Clavero, D. A. Antoniadis and **J. A. del Alamo**, “A Scaling Study of Excess OFF-State Current in InGaAs Quantum-Well MOSFETs,” *IEEE Transactions in Electron Devices*, 2018. (Submitted)
2. Y. Lin, Q. Ma, P.-C. Shen, Y. Bie, A. Liao, B. Han, N. Mao, X. Zhang, X. Ji, Y. Zhang, J. Yin, S. Huang, M. Dresselhaus, P. Jarillo-Herrero, X. Ling, **J. Kong** and T. Palacios, “Asymmetric Hot-Carrier Thermalization and Broadband Photoresponse in Graphene-2D Semiconductor Lateral Heterojunctions,” 2018. (Submitted)
3. M. Stone, B. Navarette, K. Luongo, A. Hadjikhani, P. Wang, J. Hong, **J. Bokor** and **S. Khizroev**, “Anomalous magnetoresistance oscillations in magnetic tunneling junctions with embedded magnetic metal nanoparticles,” *Appl. Phys. Lett.*, 2018. (Submitted)
4. S. K. Vadlamani, S. Agarwal, D. T. Limmer and **E. Yablonovitch**, “Tunnel-FET Switching is Governed by Non-Lorentzian Spectral Line-Shape,” *Proceedings of the IEEE*, 2018. (Submitted)
5. A. Vidaña, **D. Zubia**, M. Martinez, E. Acosta, J. Mireles Jr., **T.-J. K. Liu**, S. Almeida, “Conductivity modulation in strained transition-metal-dichalcogenides via micro-electro-mechanical actuation,” *Semiconductor Science and Technology*, 2018. (Submitted)
6. X. Zhang, J. Grajal, U. Radhakrishna, X. Wang, W. Chern, L. Zhou, Y. Lin, P.-C. Shen, X. Ji, X. Ling, A. Zubair, Y. Zhang, H. Wang, M. Dubey, **J. Kong**, M. S. Dresselhaus and T. Palacios, “Two-dimensional MoS2-enabled Rectenna for Ubiquitous Energy Harvesting in the Wi-Fi Band,” 2018. (Submitted)

Conference Proceedings: Major Conferences *(chronological)*

1. S. Kim, P. Zheng, K. Kato, L. Rubin, **T.-J. K. Liu**, “Cost-Efficient Sub-lithographic Patterning with Tilted-Ion Implantation (TII),” *International Symposium on VLSI Technology, Systems, and Applications (2018 VLSI-TSA)*, Hsinchu, Taiwan, Apr 2018.
2. A. El-Ghazaly, C. H. Lambert, B. Tran, A. Pattabi, J. Gorchon, **S. Salahuddin**, **H.-S. P. Wong** and **J. Bokor**, "Scaling of All-Optical Switching to Nanometer Dimensions," *IEEE International Magnetics Conference (Intermag)*, Singapore, Apr 2018.
3. J. Hong, O. Lee, K. Dong, **S. Khizroev**, L. You, and **J. Bokor**, “Probe-based Spin Torque Transfer Device for Writing Hard Disks,” *IEEE International Magnetic Conference (Intermag)*, Singapore, Apr 2018.
4. K. Han, S. Fortuna, M. Amani, S. Desai, D.-H. Lien, G. H. Ahn, **E. Yablonovitch**, **A. Javey** and **M. C. Wu**, “Bright Electroluminescence from Back-Gated WSe2 P-N Junctions Using Pulsed Injection,” *CLEO*, May 2018.
5. N. M. Andrade, S. Hooten, S. A. Fortuna, K. Han, **E. Yablonovitch** and **M. C. Wu**, “Inverse Design for Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based NanoLED,” *CLEO*, May 2018.
6. S. Hooten, N. Andrade, S. A. Fortuna, K. Han, **M. C. Wu** and **E. Yablonovitch**, “Hybrid Metallo-Dielectric Structure for Spontaneous Emission Enhancement,” *CLEO*, May 2018.
7. N. M. Andrade, K. T. Settaluri, S. Fortuna, S. Hooten, K. Han, **E. Yablonovitch**, **V. Stojanović**, **M. C. Wu**, "Optical Antenna NanoLED Based Interconnect Design," *IEEE Photonics Conference*, Reston, VA, Oct 2018.
8. F. Niroui, J. Han, M. Saravanapavanantham, **J. H. Lang** and **V. Bulović**, “From nanostructured building blocks to active devices,” *IEEE MEMS Workshop*, 2018. (Accepted)
9. Z. A. Ye, S. Almeida, M. Rusch, A. Perlas, W. Zhang, U. Sikder, J. Jeon, V**. Stojanović** and **T.-J. K. Liu**, “Demonstration of Sub-50 mV digital integrated circuits with microelectromechnical relays,” *IEEE International Electron Devices Meeting*, San Francisco, CA, Dec 2018. (Accepted)
10. C. Bi, X. Li and **S. X. Wang**, “Interfacial control of W/CoFeB/MgO multilayers for high-density SOT-MRAM”, *IEEE International Electron Devices Meeting*, San Francisco, CA, Sep 2018. (Submitted)

Conference Proceedings: Other Conferences *(chronological)*

1. **J. A. del Alamo**, X. Cai, W. Lu, A. Vardi and X. Zhao, “III-V CMOS: Quo Vadis?” Invited Talk at *Joint International EUROSOI Workshop and International Conference on Ultimate Integration on Silicon (EUROSOI-ULIS 2018)*, Granada, Spain, March 19-21, 2018.
2. **J. A. del Alamo**, X. Cai, W. Lu, A. Vardi and X. Zhao, “III-V CMOS: Quo Vadis?” Invited Talk at *Compound Semiconductor Week (CSW 2018)*, Cambridge, Massachusetts (U.S.), May 29-June 1, 2018.
3. A. Vardi and **J. A. del Alamo**, “Fin-Width Scaling of Highly-Doped InGaAs Fins,” *Compound Semiconductor Week (CSW 2018)*, Cambridge, Massachusetts (U.S.), May 29-June 1, 2018.
4. X. Zhao, A. Vardi and **J. A. del Alamo**, “Modeling the Parasitic Bipolar Effect in InGaAs FinFETs,” *Compound Semiconductor Week (CSW 2018)*, Cambridge, Massachusetts (U.S.), May 29-June 1, 2018.
5. **L. K. Marlor** and **C. T. Amelink**, “The Development of a Context-based Summer Research Program for Community College Faculty in Science and Engineering,” *2018 American Society for Engineering Education Annual Conference & Exposition*, Salt Lake City, UT, June 2018.

6. S. Hooten, N. M. Andrade, S. A. Fortuna, K. Han, **M. C. Wu**, and **E. Yablonovitch**, “Metal-Dielectric Structure for Spontaneous Emission Enhancement of Point Radiation Sources,” in *International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, July 2018.
7. K. Han, S. Fortuna, M. Amani, S. Desai, D.-H. Lien, G.H. Ahn, **E. Yablonovitch**, **A. Javey**, **M.C. Wu**, "Pulsed injection of monolayer WSe2 light-emitting diodes," in *International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, July 2018.
8. S. A. Fortuna, C. Heidelberger, N. Andrade, K. Han, S. Hooten, **E. Yablonovitch**, **E. A. Fitzgerald**, **M. C. Wu**, "Fast Spontaneous Emission in a III-V Antenna-LED", *International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, July 2018.
9. C. Bi, N. Sato, R. Cheaito, R. M. White, M. Asheghi, K. E. Goodson and **S. X. Wang**, “Ultrafast 3-Terminal and 2-Terminal MRAM enabled by Spin-Orbit Torque or Thermally Assisted Switching,” *2018 IEEE Magnetic Recording Conference (TMRC)*, Western Digital Milpitas Campus. August 9, 2018.
10. S. A. Fortuna, C. Heidelberger, **E. Yablonovitch**, **E. A. Fitzgerald**, **M. C. Wu**, "Nanoscale III-V light emitting diode with antenna-enhanced 250 picosecond spontaneous emission lifetime", *International Semiconductor Laser Conference*, Sante Fe, NM, September, 2018.
11. **J. A. del Alamo**, X. Zhao, W. Lu, A. Vardi and X. Cai, “Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs,” Invited Plenary Talk at *IEEE Nanotechnology Materials and Devices Conference (NMDC)*, Portland, OR, October 14-17, 2018.

1aii. *Books and Book Chapters (alphabetized by first author)*

1. C. Bi, N. Sato, and **S. X. Wang**, “Spin-orbit torque magnetoresistive random-access memory (SOT-MRAM),” in *Advances in Non-volatile Memory and Storage Technology*, Editors: Y. Nishi and B. Magyari-Köpe, Elsevier, 2018 (in revision).
2. R. O. Tapaloglu and H.-S. P. Wong (eds), “Beyond-CMOS Technologies for Next Generation Computer Design,” Springer, 2018.
3. The nanomechanics chapter of E3S e-book has been finished in this period and will be published on nanoHUB.org shortly.

1aiii. *Other Non-Peer Reviewed Publications (alphabetized by first author)*

X. Zhao, W. Lu, A. Vardi and **J. A. del Alamo**, “Shrinking the vertical nanowire MOSFET,” *Compound Semiconductor Magazine*, vol. 24 (4), pp. 52-56, June 2018.

1b. *Conference Presentations (in alphabetical order)*

Talks: *(excluded are period 10 talks that have published proceedings; see pp. 114-115)*

1. P.-C. Shen, Y. Lin, T. Palacios, and J. Kong, “Unraveling the Effect of Multiple Defect States in Synthetic Monolayer MoS2 Through Electronic and Optical Probes,” *APS March Meeting*, Los Angeles, March 5-9, 2018.
2. T. Cao, “Unifying Optical Selection Rules for Excitons in Two Dimensions: Band Topology and Winding Numbers,” *2018 American Physical Society (APS) March Meeting*, Los Angeles, California, March 6, 2018.

3. F. Zhao, “Electric Polarization and End States in Boron Nitride Nanoribbons,” *2018 American Physical Society (APS) March Meeting*, Los Angeles, California, March 7, 2018.
4. R. Wilson, Y. Yang, J. Gorchon, C.-H. Lambert, S. Salahuddin, and J. Bokor, "Picosecond electrical excitation of ultrafast magnetization dynamics in ferro-and ferrimagnetic metals." *APS March Meeting*, Los Angeles, CA, March 2018.
5. S. G. Louie, “Topological Effects in Atomically Thin One- and Two-Dimensional Semiconductors,” *Symposium on Materials Science and Technology toward Energy-Saving Society (MASTES2018)*, Tokyo, Japan, March 12, 2018.
6. J. Bokor, “Novel Approaches for MRAM Speedup,” *Lam Research Technical Symposium*, Beijing, China, March 2018.
7. S. G. Louie, “Interaction and Topological Effects in Atomically Thin Two-dimensional Materials,” *32nd International Winterschools on Electronic Properties of Novel Materials (IWEPNM2018)*, Kirchberg, Austria, March 22, 2018.
8. J. Wu, “Phase transition materials for microactuation”, *MRS Spring Meeting*, Phoenix, AZ, April 2018.
9. T.-J. K. Liu, “Innovation: Key to the Future of Moore’s Law,” *National Academy of Inventors 2018 Annual Conference*, Washington DC, April 4, 2018.
10. S. G. Louie, “The Fascinating Quantum World of Two-dimensional Materials: Symmetry, Interaction and Topological Effects,” *2018 Brazilian Physical Society Meeting*, Foz do Iguacu, Brazil. May 9, 2018.
11. W. Hwang, W. Wan, S. Mitra, and H.-S. P. Wong “Coming Up N3XT, After 2D Scaling of Si CMOS,” *IEEE International Symposium on Circuits and Systems (ISCAS)*, Florence, Italy, May 27-30, 2018.
12. V. Stojanovic “Creating Intelligence at the Edge with new materials and device technologies,” *AMAT ET Conference*, Las Vegas, NV, June 2018.
13. S. G. Louie, “Interaction and Topological Effects in Atomically Thin 1D and 2D Semiconductors,” *Symposium on Practical Quantum Mechanics for Electronic Materials*, Austin, Texas, June 2, 2018.
14. F. Fischer, “Band Engineering and Quantum Confinement Effects in Graphene Nanoribbons” *2nd From Carbon-Rich Molecules to Carbon-Based Materials Conference*, Nassau Bahamas, June 8, 2018.
15. S. G. Louie, “Ab initio quantum studies of excited state phenomena in materials: Interaction and Topological effects,” *Symposium on Materials Genome Towards Exascale*, Spetses, Greece, June 12, 2018.
16. H.-S. P. Wong, “The End of the Road for 2D Scaling of Silicon CMOS and the Future of Device Technology,” *Device Research Conference (DRC)*, Santa Barbara, CA, June 24-27, 2018.
17. S. G. Louie, “Topological and Interaction Effects in Atomically Thin 1D and 2D Materials,” *International Conference on Novel 2D Materials Explored via Scanning Probe Microscopy and Spectroscopy (2DSPM)*, San Sebastian, Spain, June 25, 2018.
18. J. Kong, “Defects in 2D materials,” *NT18 Conference*, Beijing, China, July 2018.
19. S. G. Louie, “Symmetry, Interaction and Topological Effects in Atomically Thin 1D and 2D Materials,” *20th National Conference on Condensed Matter Theory and Statistical Physics of China*, Chengdu, China, July 15, 2018.

20. S. G. Louie, “Topological and Interaction Effects in Atomically Thin 1D and 2D Materials” *20th International Conference on Superlattices, Nanostructures and Nanodevices (ICSNN2018),* Madrid, Spain, July 23, 2018.
21. D. Zubia, A. Vidaña, M. Martinez, E. Acosta, S. Almeida, T.-J. King Liu, J. Mireles, "Conductivity Modulation in Strained 2D Materials via MEMS," *International Materials Research Congress*, Cancun, Mexico, August 22, 2018.
22. S. G. Louie, “Topological and Interaction Effects in Atomically Thin 1D & 2D Materials,” *Condensed Matter Physics Conference in Honor of Stephen Fahy’s Sixtieth Birthday (SFSB 2018)*, Cork, Ireland, August 30, 2018.
23. J. Bokor, “Ultrafast Spintronics Technology,” *Joint European Magnetics Symposium*, Mainz, Germany, Sep 2018.
24. F. Fischer, “There’s plenty of space at the bottom…just no room for error” *Packard Fellows Meeting*, San Diego, September 8, 2018.
25. S. Khizroev, “Tunability using multilefforics” *AFOSR Workshop on Origami Antennas*, Miami, FL, September 13, 2018.
26. F. Fischer, “There’s plenty of space at the bottom…just no room for error” *Frontiers of Molecular Engineering RSC*, September 28, 2018.
27. J. Bokor, “Picosecond Magnetic Switching by Pure Charge Current Pulses,” *Magnetic Single Nano-Object Workshop & School*, Nancy, France, Sep 2018.
28. J. Bokor, “Picosecond Magnetic Switching By Pure Charge Current Pulses,” *Ultrafast Spintronics Workshop*, Mainz, Germany, Oct 2018.
29. S. G. Louie, “New Ab Initio Many-body Approaches to Excited-State Phenomena for Quantum Energy,” *8th International Workshop on Quantum Energy*, Kunming, China, October 17, 2018.
30. T.-J. K. Liu, “The Future of Microelectronics: Beyond Transistor Scaling,” plenary talk, *Department of Energy Basic Research Needs in Microelectronics Workshop*, Bethesda, Maryland, October 23, 2018.
31. S. G. Louie, “Topological and Interaction Effects in Atomically Thin 1D & 2D Materials,” *21st Asian Workshop on First-Principles Electronic Structure Calculations*, Daejon, Republic of Korea, October 29, 2018.

Posters

1. N. C. Rodriguez, A. Vidana, S. Almeida, and D. Zubia, "CHF3/Ar Plasma Reactive Ion Etching of LTO Mask to Transfer 2D TMD onto MEMS Device," *2018 Emerging Researchers National (ERN) Conference in STEM*, Washington, DC, February 22-24, 2018.
2. S.A. Fortuna, K. Han, N. Andrade, and M.C. Wu, "High-speed nanoLED with Antenna Enhanced Light Emission," *Berkeley Sensor & Actuator Center*, Berkeley, CA. Mar 2018.
3. K. Han, S.A. Fortuna, S. Desai, M. Amani, A. Javey, E. Yablonovitch, and M.C. Wu, "Optical Antenna Based NanoLED," *Berkeley Sensor & Actuator Center*. Berkeley, CA, Mar 2018.
4. N. M. Andrade, S. A. Fortuna, K. Han, and M. C. Wu, “Efficient Waveguide-Coupling of Electrically Injected Optical Antenna Based nanoLED,” *Berkeley Sensor & Actuator Center*, Berkeley, Mar. 2018.

5. P.-C. Shen, Q. Ji, Y. Guo, J.-H. Park, Y. C. Lin, and J. Kong, “Diverse CVD Transition Metal Dichalcogenides and Their Applications”, *The Future of Nanoscale Electronics Symposium*, MIT, April 2018
6. Zhao, A. Vardi and J. A. del Alamo, “Modeling the Parasitic Bipolar Effect in InGaAs FinFETs.” *Compound Semiconductor Week (CSW 2018)*, Cambridge, MA, May 29-June 1, 2018.
7. S. G. Louie, “Novel and Unifying Optical Selection Rules for Excitons in 2D Materials: Band Topology and Winding Numbers,” *34th International Conference on the Physics of Semiconductors (ICPS2018)*, Montpellier, France, July 31, 2018.
8. R. Zubia, M. Martinez, A. Vidaña, E. Acosta, D. Zubia, and J. Mireles, “Design and Simulation of Nanoscale Electro-Mechanical Device for Information Processing,” *Summer Research Symposia*, El Paso, TX, August 2018.
9. K. Han, S.A. Fortuna, S. Desai, M. Amani, A. Javey, E. Yablonovitch, and M.C. Wu, "Optical Antenna Based NanoLED," *Berkeley Sensor & Actuator Center*, Berkeley, CA, Sep 2018.
10. N. M. Andrade, S. A. Fortuna, K. Han, and M. C. Wu, “Efficient Waveguide-Coupling of Electrically Injected Optical Antenna Based nanoLED,” *Berkeley Sensor & Actuator Center*, Berkeley, Sept. 2018.
11. K. Han, S.A. Fortuna, S. Desai, M. Amani, A. Javey, E. Yablonovitch, and M.C. Wu, "TMDC Based nanoLEDs for High-Speed Energy-Efficient Optical Interconnects," *Berkeley Emerging Technologies Research (BETR) Center Workshop*, Berkeley, CA, Sep 2018.
12. S.A. Fortuna, K. Han, N. Andrade, and M.C. Wu, "High-speed nanoLED with Antenna Enhanced Light Emission," *Berkeley Sensor & Actuator Center*, Berkeley, CA. Sep 2018.
13. K. Han, S.A. Fortuna, S. Desai, M. Amani, A. Javey, E. Yablonovitch, and M.C. Wu, "Optical Antenna Based NanoLED," *IDTechEx Show 2018*, Santa Clara, CA, Nov 2018.

1c. Other Dissemination Activities (in chronological order)

1. F. Fischer, “There’s plenty of space at the bottom…just no room for error” University of Nevada Reno, Department of Chemistry Seminar, February 23, 2018.
2. S. G. Louie, “Ab initio Theory and Computation of Multiple-Particle Correlated Excitations in Materials: Trions and Biexcitons” 2018 Materials Genome Initiative (MGI) PI Meeting, University of Maryland, College Park, Maryland, March 26, 2018.
3. J. Wu, “Materials Demo Station,” Cal Day, Berkeley, CA, April 2018.
4. J. Bokor, “Ultrafast Spintronics,” UC Santa Cruz, ECE Department Seminar, April 2018
5. F. Fischer, “There’s plenty of space at the bottom…just no room for error” University of Michigan, Department of Chemistry Seminar, April 4, 2018.
6. S. G. Louie, “The Fascinating Quantum World of Two-dimensional Materials: Symmetry, Interaction and Topological Effects,” Gail and Jeffrey Kodosky Lecture, Rensselaer Polytechnic Institute, Troy, New York, April 11, 2018.
7. F. Fischer, “There’s plenty of space at the bottom…just no room for error” University of California Los Angeles, Department of Chemistry Seminar, April 12, 2018.
8. J. A. del Alamo, “III-V CMOS: Quo Vadis.” National University of Singapore, Singapore, April 18, 2018.
9. D. Zubia, "NanoMaterials Integration Lab: Capability and Research," Texas Instruments, Dallas Texas, April 24, 2018.

10. S. G. Louie, “The Fascinating Quantum World of Two-dimensional Materials: Symmetry, Interaction and Topological Effects,” Physics Colloquium, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil, May 4, 2018.
11. T.-J. K. Liu, “Innovation: Key to the Future of Moore’s Law,” Xidian University, Xi’an, Shaanxi Province, China, May 7, 2018.
12. T.-J. K. Liu, “Innovation: Key to the Future of Moore’s Law,” Tsinghua University, Beijing, China, May 9, 2018.
13. D. Zubia, "NanoMaterials Integration Lab: Capability and Research," Instituto Politecnico Metropolitano, Medellin, Colombia, May 16, 2018.
14. S. G. Louie, “Symmetry, Interaction and Topological Effects in Atomically Thin 1D and 2D Materials,” Physics Colloquium, University of Science and Technology of China, Hefei, China, July 15, 2018.
15. S. G. Louie, “Ab initio Theory and Computation of Excited-State Phenomena at C2SEPEM: Trions, Biexcitons, and Shifted Currents,” Department of Energy’s 2018 Theoretical Condensed Matter Physics PIs Meeting, Gaithersburg, MD, August 14, 2018.
16. T.-J. K. Liu, “There’s Plenty of Room at the Top,” Nano seminar, UC Berkeley, Berkeley, CA, August 24, 2018.
17. J. A. del Alamo, “Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs.” SMIC, Shanghai, China, Sept. 10, 2018.
18. J. A. del Alamo, “Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs.” Zhejian University, Hangzhou, China, Sept. 11, 2018.
19. J. A. del Alamo, “Nanoscale III-V Electronics: InGaAs FinFETs and Vertical nanowire MOSFETs.” Lam Research Technical Symposium, Beijing, China, September 12-13, 2018.
20. J. A. del Alamo, “III-V Vertical Nanowire MOSFETs.” Semiconductor Research Corporation GRC Technology Transfer e-Workshop, Oct. 10, 2018.
21. J. Kong, “Chemical vapor deposition synthesis and transfer of two dimensional materials”, MIT Graphene Center Review, November 2, 2018.

2. *Awards & Honors*

Recipient	**Reason for Award**	**Award Name**	**Sponsor**	**Date**	**Award Type**
Erin Brooks		NSF Graduate Research Fellowship	NSF	April 2018	Scientific
Tsu-Jae King Liu	Inventions	Fellow, National Academy of Inventors	National Academy of Inventors	March 2018	Scientific
Eli Yablonovitch	Inventions	Fellow, National Academy of Inventors	National Academy of Inventors	March 2018	Scientific
Connie Chang-Hasnain	Lifetime achievement	Member, National Academy of Engineering	National Academy of Engineering	February 2018	Scientific
Steven G. Louie	Outstanding research	Gail and Jeffrey L. Kodosky ’70	Gail and Jeffrey L.	April 2018	Scientific

		Distinguished Lecturer	Kodosky Foundation		
Ting Cao	Outstanding research	Jackson C. Koo Award	Mrs. Jackson C. Koo. Dr. Jackson C. Koo	May 2018	Scientific
Ting Cao	Research	Stanford GLAM fellowship	Stanford University	December 2017	Scientific
Timothy Swager	To support transformative basic research in topic areas of interest to the DoD	Vannevar Bush Faculty Fellowship	DOD	April 2018	Scientific
Shan X. Wang		Leland T. Edwards Professorship	Stanford/ William Edwards	Oct 2018	Scientific
Junqiao Wu	Outstanding Research	Fellow	American Physical Society	September 2018	Scientific
Nicolas Andrade		Best Paper 3rd place	IEEE Photonics Conference	October 2018	Scientific
Nicolas Andrade		Best Poster 2nd place	iNOW	July 2018	Scientific
Kevin Han	One of 10 best papers for iNOW 2018	iNOW 2018 scholarship	iNOW Steering Committee	May 2018	Scientific

3. *Graduates*

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Edgar Acosta	B.S., EE	December 2017	4	Master Student, UTEP
Dongsung Choi	M.S., EECS	February 2017	1.5	Physics Ph.D., MIT
Mariana Martinez	B.S., EE	December 2016	4	Master Student, UTEP

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree*	Placement
Matthew D'Asaro	Ph.D., EECS	June 2017	7	Sea-Bird Electronics
Ali Hadjikhani	Ph.D., ECE	December 2016	5	University of Connecticut
Chris Heidelberger	Ph.D., DMSE	August 2017	5	MIT Lincoln Laboratories

Farnaz Niroui	Ph.D., EECS	August 2017	4	Postdoc, UC Berkeley then MIT faculty
Wade Perkins	Ph.D.	May 2017	5	Intel
Emmanuel Stimphil	Ph.D., ECE	December 2017	4	Moffitt Cancer Research Center
Chuang Qian	Ph.D., EECS	May 2016	4	Samsung Electronics
Yang Yang	Ph.D.	May 2017	5	Intel
Xin Zhao	Ph.D., MSE	June 2017	6	Postdoc, MIT

Postdocs

Name	Departure Date	Placement (where did they go?)
Valerio Adinolfi	August 2017	Intermolecular
Saniya Deshpande	March 2017	Rigetti Quantum Computing
Jeongmin Hong	August 2016	JS Nanotechnologies
Jean Anne Incorvia	July 2017	University of Texas at Austin
Alexandra Rodzinski	January 2018	Rice University
Bivas Saha	January 2018	Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR)

4. *General Outputs of Knowledge Transfer Activities*

Patents:

Patent Name	Inventors/Authors	Number	Application Date	Receipt Date
Instantly rechargeable battery	S. Khizroev and R. Guduru	US Patent 10,008,962	May 2, 2017	July 26, 2018
Electromechanical Device	V. Bulovic, J. H. Lang, H. S. Lee, T. M. Swager, T. L. Andrew, M. E. D'Asaro, P. Deotare, A. Murarka, F. Niroui, E. Sletten, A. I. J. Wang	9991076		June 5, 2018.

Other Outputs of Knowledge Transfer Activities:

- **Jing Kong** (*MIT*) has formed a partnership with Applied Materials for characterizing and evaluating the 2D materials synthesized by the Applied Materials R&D team.
- **Vladimir Stojanović** (*Berkeley*) is in discussion about a joint research project with Applied Materials and has presented a talk at Applied Material's 2018 Engineering and Technology (ET) Conference.
- **Jesus del Alamo** (*MIT*) has a continued partnership with Lam Research to conduct laboratory evaluation of the high aspect ratio digital etch technology for broader semiconductor applications.
- **Jeffrey Bokor** (*Berkeley*) had multiple contacts with Lam Research about joint projects and participated in the 2018 Lam Research Symposium.

- Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) is an elected Board of Directors member at Intel Corporation.
- **Jing Kong** (*MIT*) and **Philip Wong** (*Stanford*) had multiple visits and research discussions about joint projects with TSMC.
- Former E3S investigator **Philip Wong** (Stanford) is now a vice president at TSMC.
- **David Zubia** (*UTEP*) presented a research seminar at Texas Instruments, Dallas, to discuss potential research projects for the Stritch project.
- Turning Point Brands has awarded **Sakhrat Khizroev** (*FIU*) a monetary industry award to comparatively study primary and secondary battery cells based on magnetoelectric nanoparticles

5a. Participants

In the current reporting period, the Center has 120 participants. Funding of faculty, postdoctoral, graduate student, and undergraduate student participants is summarized as follows.

Period 9	**Summer**	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	12	1	0	10	23

	Funded by E3S			**Other Funding Source**	**Total Participants**
Category	50% or more	Less than 50%	**Total**		
Postdocs	8	1	**9**	2	**20**
Grad Students	19	5	**24**	8	**43**
Undergrads	2	23	**25**	0	**25**
TOTAL					**88**

PARTICIPANTS - PERIOD 9

Category		**Institutional Affiliation**		**Department**		**Gender**		**Disability Status**		**Ethnicity**		**Race**		**Veteran**		**Citizenship**	
23	Faculty	11	Berkeley	18	E.E.	20	M	0	Hearing Impairment	2	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	18	US Citizens
		7	MIT	2	Mats Sci	3	F	0	Visual Impairment	18	Not Hispanic or Latino	5	Asian	23	No	5	Permanent Resident
		1	Stanford	2	Chemistry			0	Mobility/Orthopedic Impairment	3	Decline to State	0	Black or African American			0	Other non-US Citizen
		1	UTEP	1	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		1	LATTC					21	None			16	White			0	Not Available
		1	FIU					2	Decline to State			2	Decline to State				
		1	Other					0	Not Available			0	Not Available				
20	Postdocs	13	Berkeley	18	E.E.	14	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	0	Yes	4	US Citizens
		3	MIT	0	Mats Sci	6	F	0	Visual Impairment	18	Not Hispanic or Latino	11	Asian	20	No	1	Permanent Resident
		2	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American			14	Other non-US Citizen
		1	UTEP	2	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		1	FIU					20	None			9	White			1	Not Available
								0	Decline to State			0	Decline to State				
								0	Not Available			0	Not Available				
43	Graduate Students	30	Berkeley	32	E.E.	37	M	0	Hearing Impairment	1	Hispanic	1	American Indian or Alaskan Native	0	Yes	24	US Citizens
		9	MIT	4	Mats Sci	6	F	0	Visual Impairment	41	Not Hispanic or Latino	21	Asian	43	No	1	Permanent Resident
		2	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	1	Black or African American			17	Other non-US Citizen
		0	UTEP	0	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			1	Decline to State
		2	FIU	6	Chemistry			41	None			18	White			0	Not Available
				1	Other			2	Decline to State			2	Decline to State				
								0	Not Available			0	Not Available				
25	Undergraduate Students	3	Berkeley	20	E.E.	17	M	0	Hearing Impairment	6	Hispanic	0	American Indian or Alaskan Native	1	Yes	20	US Citizens
		0	MIT	1	Mats Sci	8	F	0	Visual Impairment	19	Not Hispanic or Latino	4	Asian	24	No	4	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	4	Black or African American			1	Other non-US Citizen
		6	UTEP	1	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		1	LATTC	2	ChemE			25	None			11	White			0	Not Available
		0	CCC	0	Engr Phys			0	Decline to State			4	Decline to State				
		1	FIU					0	Not Available			2	Not Available				
		14	Other														
9	Staff	8	Berkeley	0	E.E.	3	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	Yes	8	US Citizens
		1	MIT	0	Mats Sci	6	F	0	Visual Impairment	8	Not Hispanic or Latino	3	Asian	9	No	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American			0	Other non-US Citizen
		0	UTEP	8	E3S			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
			FIU	1	Other			6	None			5	White			1	Not Available
								0	Decline to State			0	Decline to State				
								1	Not Available			1	Not Available				
120	**TOTAL PARTICIPANTS**																

5b. Affiliates

AFFILIATES - PERIOD 9

Category		**Institutional Affiliation**		**Department**		**Gender**		**Disability Status**		**Ethnicity**		**Race**		**Citizenship**	
4	Faculty	2	Berkeley	3	E.E.	1	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	1	US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	1	Not Hispanic or Latino	1	Asian	0	Permanent Resident
		0	Stanford	0	Physics	1 NA		0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	1	Other non-US Citizen
		1	UTEP	1	Chemistry			0	Other	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			2	None			1	White	2	Not Available
		0	CCC	0	Other			0	Decline to State			0	Decline to State		
		1	Other					2	Not Available			2	Not Available		
0	Research Scientists & Visiting Faculty	0	Berkeley	0	E.E.	0	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	0	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU					0	None			0	White	0	Not Available
								0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
6	Postdocs	5	Berkeley	4	E.E.	5	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		1	MIT	0	Mats Sci	0	F	0	Visual Impairment	4	Not Hispanic or Latino	1	Asian	0	Permanent Resident
		0	Stanford	0	Physics	1 NA		0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	4	Other non-US Citizen
		0	UTEP	0	Chemistry			0	Other	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	0	ME			4	None			2	White	0	Not Available
				0	Other			0	Decline to State			0	Latino		
				2 NA				2	Not Available			3	Not Available		
9	Graduate Students	3	Berkeley	8	E.E.	6	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	3	US Citizens
		4	MIT	0	Mats Sci	1	F	0	Visual Impairment	4	Not Hispanic or Latino	1	Asian	1	Permanent Resident
		0	Stanford	1	Physics	2 NA		0	Mobility/Orthopedic Impairment	2	Decline to State	1	Black or African American	3	Other non-US Citizen
		0	UTEP	0	Chemistry			0	Other	3	Not Available	0	Native Hawaiian or Other Pacific Islander	1	Decline to State
		6	FIU	0	ME			5	None			2	White	2	Not Available
				0	Other			1	Decline to State			2	Decline to State		
								3	Not Available			4	Not Available		
4	Undergraduate Students	2	Berkeley	3	E.E.	0	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	1	Not Hispanic or Latino	1	Asian	0	Permanent Resident
		0	Stanford	0	Physics	2 NA		0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	1	Other non-US Citizen
		1	UTEP	1	Chem			0	Other	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			2	None			1	White	2	Not Available
		0	CCC	0	Other			0	Decline to State			2	Decline to State		
		1 other						2	Not Available			0	Not Available		
Category		**Institutional Affiliation**		**Department**		**Gender**		**Disability Status**		**Ethnicity**		**Race**		**Citizenship**	
0	Staff	0	Berkeley	1	MTL	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		1	MIT	0	OEOP	0	F	0	Visual Impairment	1	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	TAP			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC					1	None			1	White	0	Not Available
								0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
23	**TOTAL AFFILIATES**														

6. *Center Partners*

	Organization Name	Organization Type	Address	Contact Name	Type of Partner	160 hours or more?
1.	Lam Research	Company	Fremont, CA	Nerissa Draeger	Research	Yes
2.	Lam Research	Company	Fremont, CA	Rick Grotto	Research	No
3.	Applied Materials	Company	Santa Clara, CA	Chris Ying	Research Collaboration	Yes
4.	Applied Materials	Company	Santa Clara, CA	John Dukovic	Knowledge Transfer	No
5.	Applied Materials	Company	Santa Clara, CA	Chong-Ping Chang	Knowledge Transfer	No
6.	ASML	Company	Veldhoven, Netherlands	Nak Seong	Research Collaboration	Yes
7.	TSMC	Company	Hsinchu, Taiwan	Randy Osborne	Research Collaboration	Yes
8.	Universidad Autonoma de Ciudad Juarez, Mexico	University	Juarez, Mexico	Professor Mireles	Research Collaboration	Yes
9.	Intel	Company	Hillsboro, OR, CA	Ian Young	Knowledge Transfer	No
10.	IBM	Company	Yorktown Heights, NY	Paul Soloman	Knowledge Transfer	No
11.	IMEC	Company	San Francisco, CA	Sam El Kazzi	Research	No
12.	CEA-LETI	French National Laboratory	Grenoble, France	Louis Hutin & Oliver Faynot	Education Knowledge Transfer	No
13.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Eboney Hearn	Education & Diversity	No
14.	MIT Office of the Dean of Graduate Education	University	Cambridge, MA	Gloria Anglon	Education & Diversity	No

15.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Merryl Owen	Education & Diversity	No
16.	UC Berkeley Summer Sessions	University	Berkeley, CA	Richard Russo	Education	No
17.	Berkeley Engineering Graduate Outreach	University	Berkeley, CA	Meltem Erol	Education & Diversity	No
18.	Berkeley Division of Equity and Inclusion	University	Berkeley, CA	Shaila Kotadia	Education & Diversity	No
19.	UC Berkeley Center for Teaching & Learning	University	Berkeley, CA	Richard Freishtat	Education	No
20.	Lawrence Hall of Science	Museum	Berkeley, CA	Lynn Tran	Education	No
21.	UC Berkeley School of Public Health	University	Berkeley, CA	Deborah Barnett	Education	No
22.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon	Education & Diversity	No
23.	UC Berkeley Science @ Cal	University	Berkeley, CA	Rachel Winheld	Education & Diversity	No
24.	University of California Office of the President	University	Oakland, CA	Pamela Jenkins	Diversity	No
25.	Program YoUr Future	Non-Profit	Berkeley, CA	Alankrita Dayal	Education & Diversity	No
26.	UC Berkeley Black Graduate Engineering and Science Students	University	Berkeley, CA	Benjamin Osoba	Education & Diversity	No
27.	Translational Applications of Nanoscale Multiferroic Systems (TANMS)	University	Los Angeles, CA	Maria del Pilar O'Cadiz	Education & Diversity	No

7. *Summary Table for Internal NSF Reporting Purposes*

1.	The number of participating institutions (all academic institutions that participate in activities at the Center).	6
2.	The number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center).	6
3.	The total current year leveraged support (sum of funding for the Center from all sources other than NSF-STC) [Leveraged funding includes both cash and in-kind support related to Center activities, but not funds awarded to individual PIs.]	$454,070
4.	The number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF).	120

8. *Media Publicity of Center*

a. **EECS Professor Chang-Hasnain named to NAE, February 2018.**
https://engineering.berkeley.edu/2018/02/eecs-professor-chang-hasnain-named-nae

b. **Two innovators elected to National Academy of Inventors, March 2018.**
http://news.berkeley.edu/story_jump/three-innovators-elected-to-national-academy-of-inventors/

c. **Tsu-Jae King Liu named new dean of Berkeley engineering, June 2018.**
   1. https://engineering.berkeley.edu/2018/06/tsu-jae-king-liu-named-new-dean-berkeley-engineering

IX. INDIRECT/OTHER IMPACTS

International Activities:

- **Eli Yablonovitch** gave talks related to Energy Efficient Electronic Systems at various locations outside the U.S., including Spain, Israel, and France.
- **Steven Louie** gave talks on low-dimensional nanosystems in Austria, Singapore, Israel, Japan, Brazil, Greece, Ireland, Republic of Korea, Spain, France, and China.
- **Jesus del Alamo** gave talks on III-V MOSFETs and TFETs for CMOS in Spain, Singapore, and China.
- **Jeffrey Bokor** gave talks on ultrafast magnetic switching in Germany, China, and France.

Education and Diversity:

- Impacted >38% of the campuses in the California Community College System: In 2012, the Center was awarded a NSF Research Experiences for Undergraduates (REU) Site to extend the E^{3}S Transfer-to-Excellence REU program to community college students outside of disciplines affiliated with the Center from five to fifteen summer students annually. The Site was renewed in 2015 and was again renewed in 2018. During the summer 2018 (Period 9), the Center hosted 13 community college students from science and engineering majors in 10 different labs on Berkeley's campus. These students research focused on robotics and biotechnology. Over the Center's lifespan, E^{3}S has hosted 103 community college students from 44 institutions from every region in the state of California. This total consists of projects advised by 44 faculty mentors and supervised by graduate student and postdoc mentors. Among the students eligible to transfer (excludes summer 2018 cohort), 93% have transferred to a 4-year institution.

- Community College Faculty: Similar to the expansion for the summer research program for community college students, the Center expanded its E^{3}S Teacher Fellows Program from two to six community college faculty with a NSF Research Experience for Teachers (RET) Site award. Beginning in Period 5, because of this new NSF award, was the implementation of curriculum development workshops on context-based learning, a pedagogical approach, which has been shown through assessments to enhance the students' interest in STEM. Closely aligned with project-based learning and inquiry-based science education, a context-based approach was selected to provide community college faculty a pedagogical method that can enhance learning, engage students, and improve the relevance of the science being taught. In Period 9, a three community college faculty from engineering and chemistry departments at Bay Area community colleges conducted a nine-week research experience in the UC Berkeley labs of V. Stojanovic, J. Wu, and E. Yablonovitch. In addition to coordinating the logistics (i.e., application, selection, placement, and implementation) for the summer RET program, the Center hosted four curriculum development workshops, three on context-based learning pedagogy and one on digital/online education with Berkeley's Center for Teaching and Learning, Berkeley Resource Center for Online Education, and School of Public Health; and Lawrence Hall of Science. Additionally, three faculty where hosted through this Site award that focused solely on curriculum development. These faculty were past participants that had already done research through the program in the past, and they worked to enhance and create curriculum. At the conclusion of the summer, these faulty members each developed a course module or lab assignment, which will be taught at their respective community college during the 2018-2019 academic year.

- HBCU REU Program: In period 5, the Center was awarded supplemental funding from the University of California, Office of the President in order to create the UCB-HBCU REU program. This award funds students to conduct summer research with UC Berkeley EE Faculty that are associated with a research center on campus (CIAN, E^{3}S, NASCENT, TANMS). The students are then able to go back to their HBCU and conduct research during the academic year at their home institutes. All 4 centers have committed to hosting the students for a second summer in their respective REU programs, so long as the student maintains eligibility. In period 9, three students (from Jackson State University) took part in this REU program. The Center managed the program, hosted the students, and incorporated them into E^{3}S REU workshops and activities.

Additional other impacts include:

- An undergraduate cognitive science major was a workstudy office assistant during this reporting period. His work in support of the Center's undergraduate programs has provided information and encouragement to him as he aspires to pursue a career in educational administration.

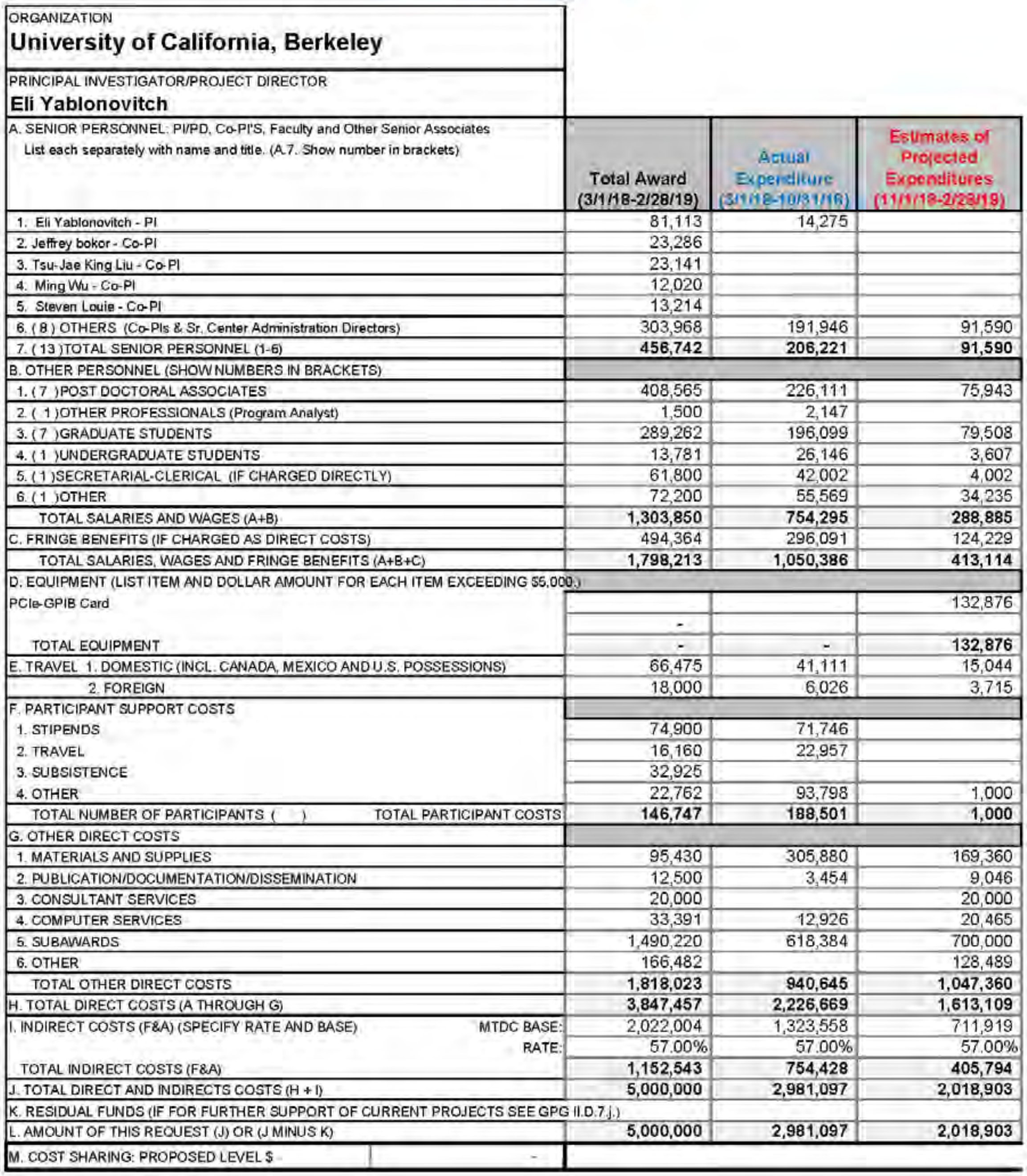
- Two former TTE REU students were workstudy office assistants during this reporting period. One of them also worked to support the Center's undergraduate programs, which has helped to inform her on different career paths and options available to her. She has also gained insight on best mentoring approaches with students of similar education background (community college) to her.

X. BUDGET

1. Current Award Year

Total spending for period 8 is approximately $5.4 million and includes applying unspent funds from period 8 (~$1.5M remaining as of 03/01/18). Total unobligated funds at the end of period 9 are estimated to be $1.1M. The following are three-column summary budget tables which reflect total NSF funding for the whole Center for the current award year. These budgets include **only NSF STC core funds.**

Current Award Year
Period 9: 3/1/18-2/28/19



ORGANIZATION
University of California, Berkeley

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Eli Yablonovitch

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Total Award (3/1/18-2/28/19)	Actual Expenditure (3/1/18-10/31/18)	Estimates of Projected Expenditures (11/1/18-2/28/19)
1. Eli Yablonovitch - PI	81,113	14,275	
2. Jeffrey bokor - Co-PI	23,286		
3. Tsu-Jae King Liu - Co-PI	23,141		
4. Ming Wu - Co-PI	12,020		
5. Steven Louie - Co-PI	13,214		
6. (8) OTHERS (Co-PIs & Sr. Center Administration Directors)	303,968	191,946	91,590
7. (13)TOTAL SENIOR PERSONNEL (1-6)	**456,742**	**206,221**	**91,590**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (7)POST DOCTORAL ASSOCIATES	408,565	226,111	75,943
2. (1)OTHER PROFESSIONALS (Program Analyst)	1,500	2,147	
3. (7)GRADUATE STUDENTS	289,262	196,099	79,508
4. (1)UNDERGRADUATE STUDENTS	13,781	26,146	3,607
5. (1)SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	61,800	42,002	4,002
6. (1)OTHER	72,200	55,569	34,235
TOTAL SALARIES AND WAGES (A+B)	**1,303,850**	**754,295**	**288,885**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	494,364	296,091	124,229
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**1,798,213**	**1,050,386**	**413,114**
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
PCIe-GPIB Card			132,876
	-		
TOTAL EQUIPMENT	**-**	**-**	**132,876**
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)	66,475	41,111	15,044
2. FOREIGN	18,000	6,026	3,715
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	74,900	71,746	
2. TRAVEL	16,160	22,957	
3. SUBSISTENCE	32,925		
4. OTHER	22,762	93,798	1,000
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS	**146,747**	**188,501**	**1,000**
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	95,430	305,880	169,360
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	12,500	3,454	9,046
3. CONSULTANT SERVICES	20,000		20,000
4. COMPUTER SERVICES	33,391	12,926	20,465
5. SUBAWARDS	1,490,220	618,384	700,000
6. OTHER	166,482		128,489
TOTAL OTHER DIRECT COSTS	**1,818,023**	**940,645**	**1,047,360**
H. TOTAL DIRECT COSTS (A THROUGH G)	**3,847,457**	**2,226,669**	**1,613,109**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	2,022,004	1,323,558	711,919
RATE:	57.00%	57.00%	57.00%
TOTAL INDIRECT COSTS (F&A)	**1,152,543**	**754,428**	**405,794**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**5,000,000**	**2,981,097**	**2,018,903**
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**5,000,000**	**2,981,097**	**2,018,903**
M. COST SHARING: PROPOSED LEVEL $ -	-		

Current Award Year
Period 9: 3/1/18-2/28/19

ORGANIZATION
Massachusetts Institute of Technology

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Vladimir Bulovic

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Total Award (3/1/18-2/28/19)	Actual Expenditure (3/1/18-10/31/18)	Estimates of Projected Expenditures (11/1/18-2/28/19)
1. Vladimir Bulovic - Professor	11,000		
2. Jesus Del Alamo - Professor	5,400		
3. Eugene Fitzgerald - Professor	9,200	10,006	
4. Jing Kong - Professor	8,250		
5. Jeffrey Lang - Professor	10,900	6,064	
6. (2) Prof. Swager & new faculty participant TBD	22,800		
7. (7)TOTAL SENIOR PERSONNEL (1-6)	**67,550**	**16,069**	**-**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. ( )POST DOCTORAL ASSOCIATES	-		
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	7,500	27,899	13,950
3. (7)GRADUATE STUDENTS	287,000	75,279	70,100
4. ( )UNDERGRADUATE STUDENTS	-		
5. (1)SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	2,000		2,000
6. (1)OTHER	6,000		6,000
TOTAL SALARIES AND WAGES (A+B)	**370,050**	**119,247**	**92,050**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	30,000	19,402	12,265
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**400,050**	**138,649**	**104,315**
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
TOTAL EQUIPMENT	**-**	**-**	**-**
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)	17,500	10,296	10,000
2. FOREIGN	-		
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	24,000	35,844	
2. TRAVEL	-		
3. SUBSISTENCE	10,000	2,310	7,690
4. OTHER	7,750		7,750
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS	**41,750**	**38,154**	**15,440**
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	35,000	31,303	75,000
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	3,320		4,000
3. CONSULTANT SERVICES	-		
4. COMPUTER SERVICES	9,000	2,139	5,000
5. SUBAWARDS	-		
6. OTHER	270,000	75,066	100,000
TOTAL OTHER DIRECT COSTS	**317,320**	**108,508**	**184,000**
H. TOTAL DIRECT COSTS (A THROUGH G)	**776,620**	**295,607**	**313,755**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	585,000		221,070
RATE:	56.00%		
TOTAL INDIRECT COSTS (F&A)	**327,600**	**115,149**	**123,799**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**1,104,220**	**410,756**	**437,554**
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**1,104,220**	**410,756**	**437,554**
M. COST SHARING: PROPOSED LEVEL $ -			

Current Award Year
Period 9: 3/1/18-2/28/19

ORGANIZATION
Stanford University

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Shan Wang

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Total Award (3/1/18-2/28/19)	Actual Expenditure (3/1/18-10/31/18)	Estimates of Projected Expenditures (11/1/18-2/28/19)
1. Shan Wang - Professor	1,929		1,929
2. Philip Wog - Professor	-	830	(830)
3.	-		-
4.	-		-
5.	-		-
6. (1) OTHERS (Sr. Research Scientist)	-		-
7. (1)TOTAL SENIOR PERSONNEL (1-6)	**1,929**	**830**	**1,099**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (1)POST DOCTORAL ASSOCIATES	42,140	15,000	27,140
2. (1)OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)			-
3. (1)GRADUATE STUDENTS	12,700	10,410	2,290
4. ( )UNDERGRADUATE STUDENTS	-		-
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	-		-
6. ( )OTHER - Tuition	8,321	6,786	1,535
TOTAL SALARIES AND WAGES (A+B)	**65,090**	**33,026**	**32,064**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	11,915	4,484	7,431
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**77,005**	**37,510**	**39,495**
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
	-		
TOTAL EQUIPMENT	**-**	**-**	**-**
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)	2,000	97	1,903
2. FOREIGN	-		
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	-		
2. TRAVEL	-		
3. SUBSISTENCE	-		
4. OTHER	-		
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS	**-**	**-**	**-**
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	2,000	1,340	660
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	-		-
3. CONSULTANT SERVICES	-		-
4. COMPUTER SERVICES	-		-
5. SUBAWARDS	-		-
6. OTHER SU NanoFabrication Faculty user fees	12,556	-	12,556
TOTAL OTHER DIRECT COSTS	**14,556**	**1,340**	**13,216**
H. TOTAL DIRECT COSTS (A THROUGH G)	**93,561**	**38,947**	**54,614**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	85,240	32,161	53,079
RATE:	58.00%	58%	58.00%
TOTAL INDIRECT COSTS (F&A)	**49,439**	**18,653**	**30,786**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**143,000**	**57,601**	**85,400**
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**143,000**	**57,601**	**85,400**
M. COST SHARING: PROPOSED LEVEL $ -			

Current Award Year
Period 9: 3/1/18-2/28/19

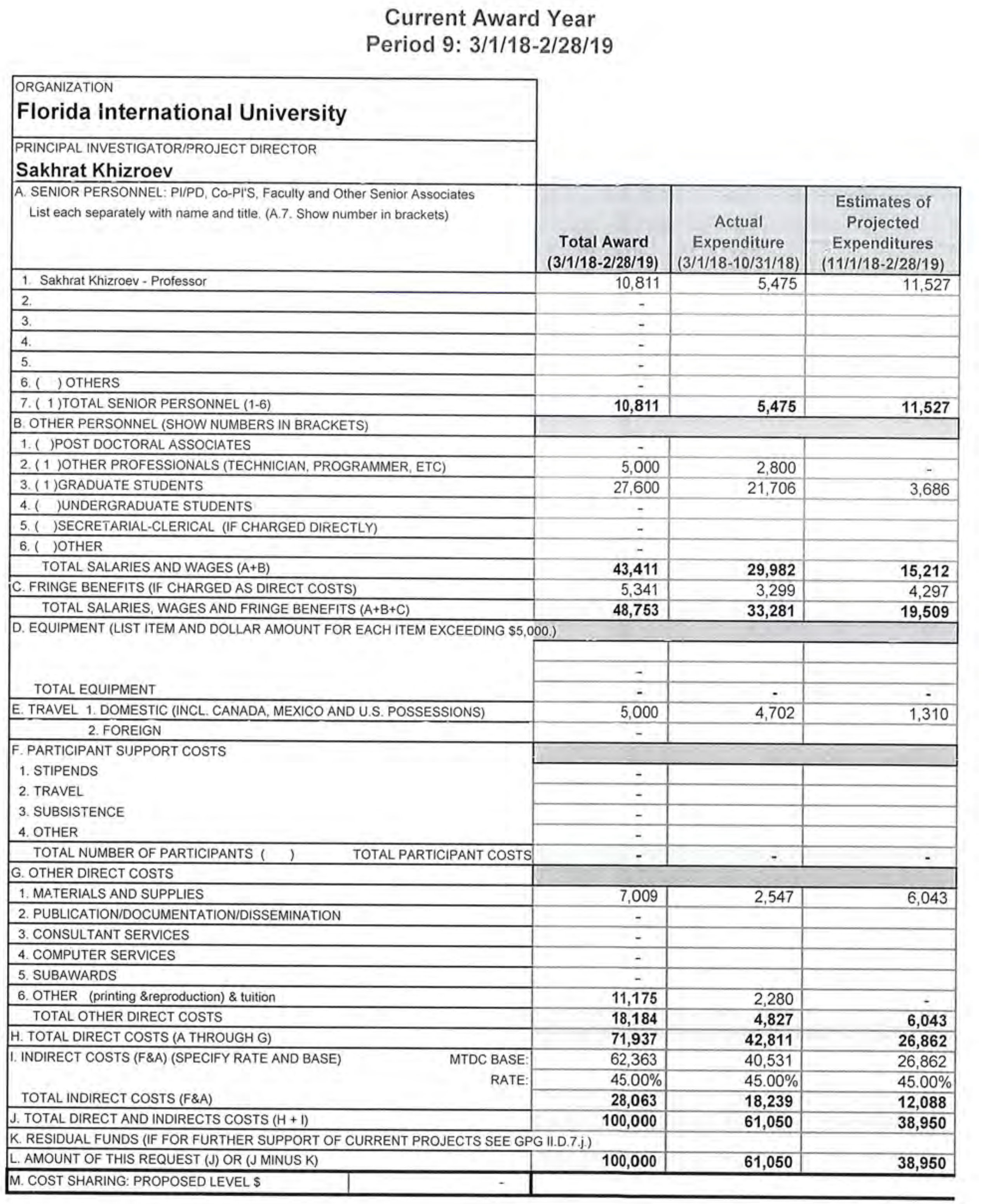
ORGANIZATION

University of Texas at El Paso

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR

David Zubia

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Total Award (3/1/18-2/28/19)	Actual Expenditure (3/1/18-10/31/18)	Estimates of Projected Expenditures (11/1/18-2/28/19)
1. David Zubia - Professor	13,056	13,056	
2.	-		
3.	-		
4.	-		
5.	-		
6. ( ) OTHERS	-		
7. (1)TOTAL SENIOR PERSONNEL (1-6)	**13,056**	**13,056**	**-**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. ( )POST DOCTORAL ASSOCIATES	-		
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	-		
3. (1)GRADUATE STUDENTS	46,500	36,500	16,000
4. ( )UNDERGRADUATE STUDENTS	-		
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	-		
6. ( )OTHER	-		
TOTAL SALARIES AND WAGES (A+B)	**59,556**	**49,556**	**16,000**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	8,585	4,406	2,000
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**68,141**	**53,961**	**18,000**
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
		135	
TOTAL EQUIPMENT	**-**	**135**	**-**
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)	6,000	4,836	4,500
2. FOREIGN	-		
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	-		
2. TRAVEL	-		
3. SUBSISTENCE	-		
4. OTHER	-		
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS	**-**	**-**	**-**
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	20,561	2,241	4,000
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	-		
3. CONSULTANT SERVICES	-		
4. COMPUTER SERVICES	-		
5. SUBAWARDS	-		
6. OTHER	-		
TOTAL OTHER DIRECT COSTS	**20,561**	**2,241**	**4,000**
H. TOTAL DIRECT COSTS (A THROUGH G)	**94,702**	**61,172**	**26,500**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	94,702	61,037	26,500
RATE:	51.00%	0.51	0.51
TOTAL INDIRECT COSTS (F&A)	**48,298**	**31,129**	**13,515**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**143,000**	**92,301**	**40,015**
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**143,000**	**92,301**	**40,015**
M. COST SHARING: PROPOSED LEVEL $	-		



Current Award Year
Period 9: 3/1/18-2/28/19

ORGANIZATION **Florida International University**			
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Sakhrat Khizroev**			
A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	**Total Award (3/1/18-2/28/19)**	**Actual Expenditure (3/1/18-10/31/18)**	**Estimates of Projected Expenditures (11/1/18-2/28/19)**
1. Sakhrat Khizroev - Professor	10,811	5,475	11,527
2.	-		
3.	-		
4.	-		
5.	-		
6. ( ) OTHERS	-		
7. (1)TOTAL SENIOR PERSONNEL (1-6)	**10,811**	**5,475**	**11,527**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. ( )POST DOCTORAL ASSOCIATES	-		
2. (1)OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	5,000	2,800	-
3. (1)GRADUATE STUDENTS	27,600	21,706	3,686
4. ( )UNDERGRADUATE STUDENTS	-		
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	-		
6. ( )OTHER	-		
TOTAL SALARIES AND WAGES (A+B)	**43,411**	**29,982**	**15,212**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	5,341	3,299	4,297
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**48,753**	**33,281**	**19,509**
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)			
	-		
TOTAL EQUIPMENT	-	-	-
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)	5,000	4,702	1,310
2. FOREIGN	-		
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	-		
2. TRAVEL	-		
3. SUBSISTENCE	-		
4. OTHER	-		
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS	-	-	-
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	7,009	2,547	6,043
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	-		
3. CONSULTANT SERVICES	-		
4. COMPUTER SERVICES	-		
5. SUBAWARDS	-		
6. OTHER (printing &reproduction) & tuition	**11,175**	2,280	-
TOTAL OTHER DIRECT COSTS	**18,184**	**4,827**	**6,043**
H. TOTAL DIRECT COSTS (A THROUGH G)	**71,937**	**42,811**	**26,862**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	62,363	40,531	26,862
RATE:	45.00%	45.00%	45.00%
TOTAL INDIRECT COSTS (F&A)	**28,063**	**18,239**	**12,088**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**100,000**	**61,050**	**38,950**
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)			
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	**100,000**	**61,050**	**38,950**
M. COST SHARING: PROPOSED LEVEL $ -			

2. *Unobligated Funds*

The following is a statement of funds estimated to remain unobligated at the end of the current award year and plans for their use.

University of California, Berkeley

Unobligated funds from the current award year are estimated to be $1.1M. These unobligated funds are projected to be spent by the end of period 10 for additional support for postdoctoral researchers and graduate student researchers, research materials and supplies, and education and outreach programs. In this regard, despite the reduced budget in period 10 ($3.7M) we plan to continue the Inter-Institutional Postdoc and the Center Rotation programs that will foster multi-institutional projects and papers by providing funding for multi-institutional postdoc positions and graduate students. Of the total unobligated funds, approximately $30K is in the participant support costs categories. The participant support funds will be used to fund a full class of participants in the Education and Diversity program in summer 2018 despite budget reductions.

Massachusetts Institute of Technology

Unobligated funds from the current award year are estimated to be $250k. These unobligated funds are projected to be spent by the end of period 10 to offset the budget reductions in period 10.

Stanford University

Funds are projected to be fully spent by the end of the current award year.

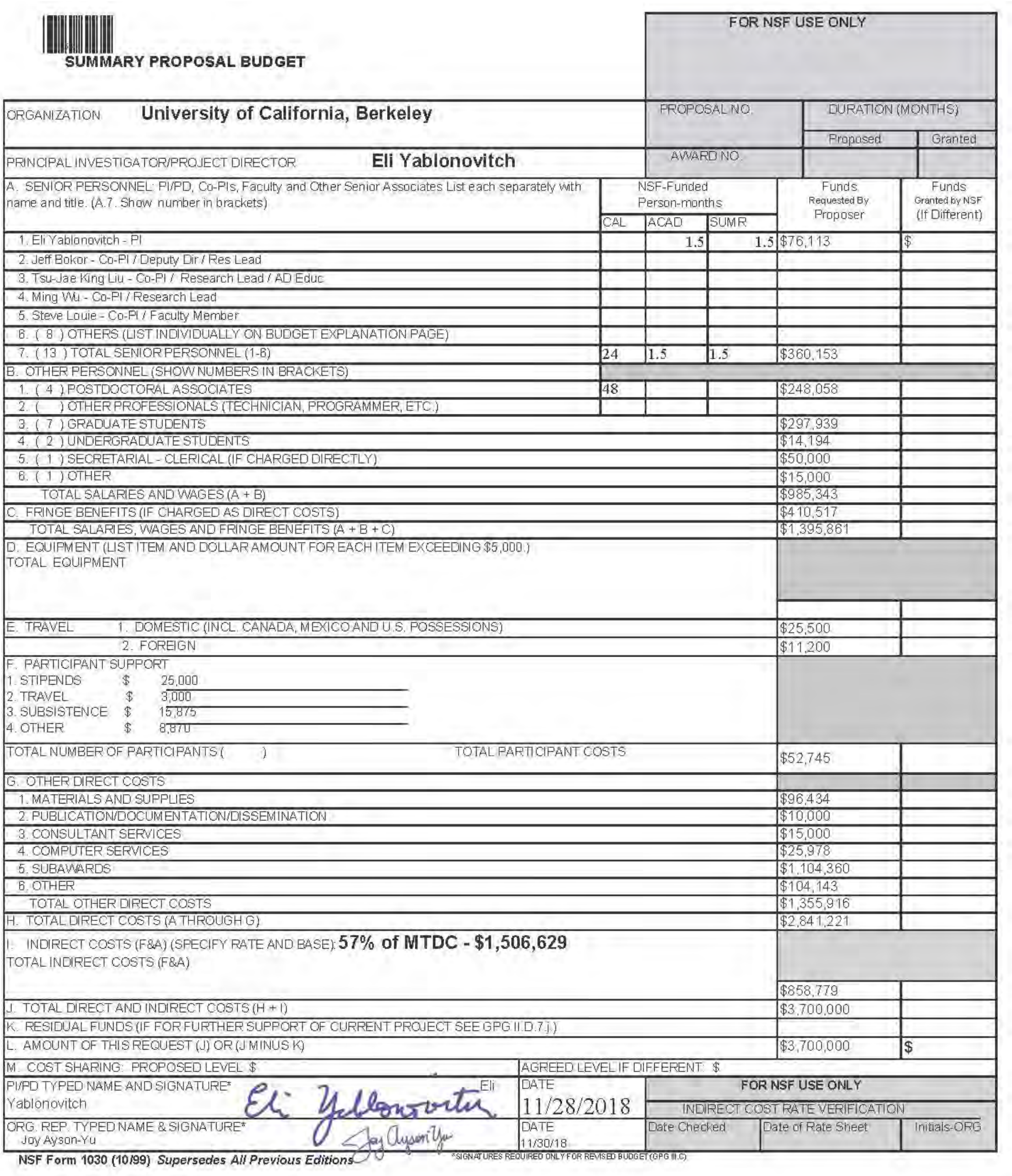
The University of Texas at El Paso

Funds are projected to be fully spent by the end of the current award year.

Florida International University

Funds are projected to be fully spent by the end of the current award year.

3. *Requested Award Year*



SUMMARY PROPOSAL BUDGET

FOR NSF USE ONLY

ORGANIZATION **University of California, Berkeley**	PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Eli Yablonovitch**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. Eli Yablonovitch - PI		1.5	1.5	$76,113	$
2. Jeff Bokor - Co-PI / Deputy Dir / Res Lead					
3. Tsu-Jae King Liu - Co-PI / Research Lead / AD Educ					
4. Ming Wu - Co-PI / Research Lead					
5. Steve Louie - Co-PI / Faculty Member					
6. (8) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (13) TOTAL SENIOR PERSONNEL (1-6)	24	1.5	1.5	$360,153	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (4) POSTDOCTORAL ASSOCIATES	48			$248,058	
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (7) GRADUATE STUDENTS				$297,939	
4. (2) UNDERGRADUATE STUDENTS				$14,194	
5. (1) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				$50,000	
6. (1) OTHER				$15,000	
TOTAL SALARIES AND WAGES (A + B)				$985,343	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$410,517	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$1,395,861	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$25,500	
2. FOREIGN				$11,200	
F. PARTICIPANT SUPPORT 1. STIPENDS $ 25,000 2. TRAVEL $ 3,000 3. SUBSISTENCE $ 15,875 4. OTHER $ 8,870					
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS				$52,745	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$96,434	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				$10,000	
3. CONSULTANT SERVICES				$15,000	
4. COMPUTER SERVICES				$25,978	
5. SUBAWARDS				$1,104,360	
6. OTHER				$104,143	
TOTAL OTHER DIRECT COSTS				$1,355,916	
H. TOTAL DIRECT COSTS (A THROUGH G)				$2,841,221	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) **57% of MTDC - $1,506,629** TOTAL INDIRECT COSTS (F&A)				$858,779	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$3,700,000	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$3,700,000	$

M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT: $			
PI/PD TYPED NAME AND SIGNATURE* Eli Yablonovitch Eli Yablonovitch	DATE 11/28/2018	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Joy Ayson-Yu Joy Ayson-Yu	DATE 11/30/18	Date Checked	Date of Rate Sheet	Initials-ORG

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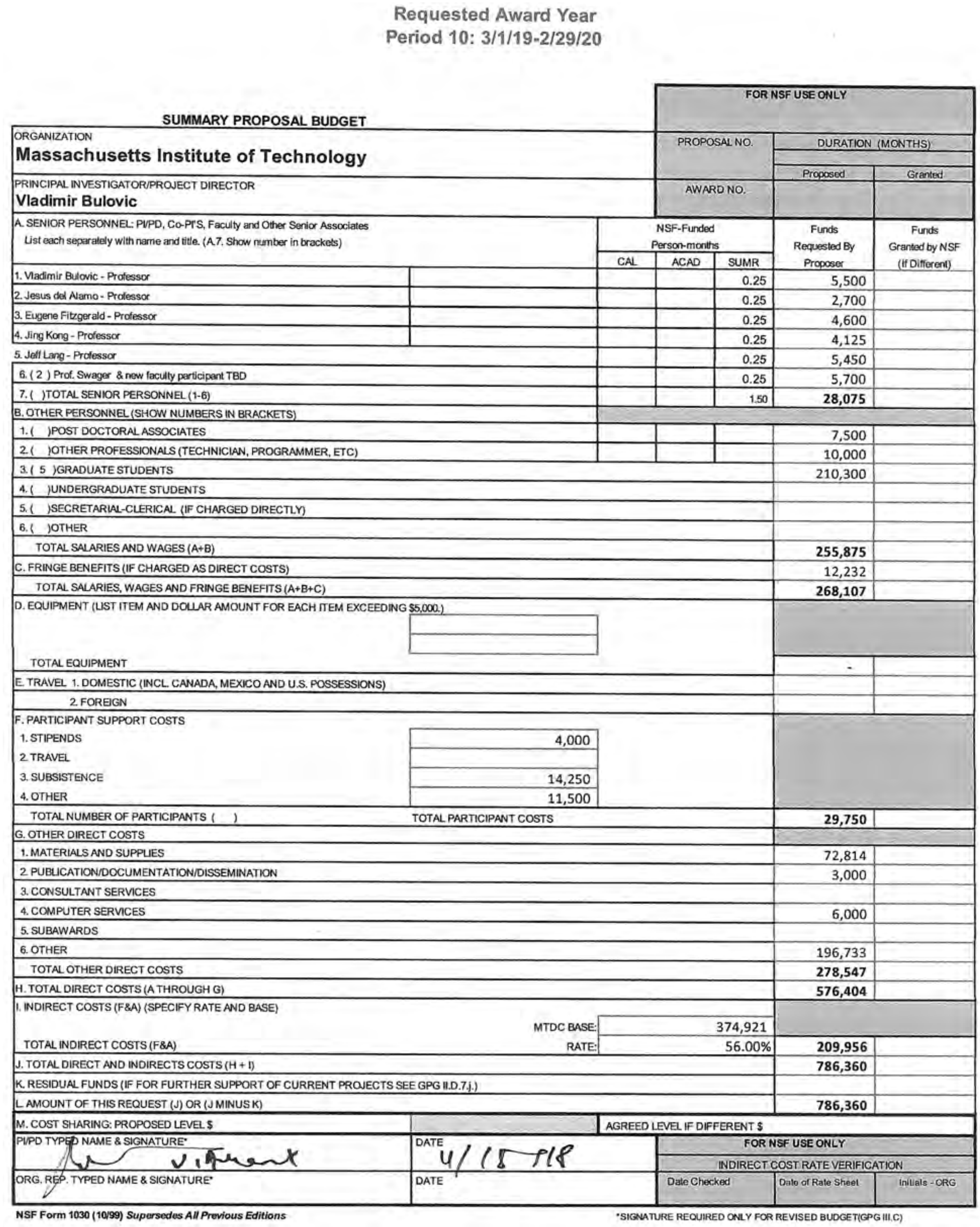
*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)



Requested Award Year
Period 10: 3/1/19-2/29/20

SUMMARY PROPOSAL BUDGET

ORGANIZATION **Massachusetts Institute of Technology**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Vladimir Bulovic**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. Vladimir Bulovic - Professor			0.25	5,500	
2. Jesus del Alamo - Professor			0.25	2,700	
3. Eugene Fitzgerald - Professor			0.25	4,600	
4. Jing Kong - Professor			0.25	4,125	
5. Jeff Lang - Professor			0.25	5,450	
6. (2) Prof. Swager & new faculty participant TBD			0.25	5,700	
7. ( )TOTAL SENIOR PERSONNEL (1-6)			1.50	**28,075**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( )POST DOCTORAL ASSOCIATES				7,500	
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)				10,000	
3. (5)GRADUATE STUDENTS				210,300	
4. ( )UNDERGRADUATE STUDENTS					
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6. ( )OTHER					
TOTAL SALARIES AND WAGES (A+B)				**255,875**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				12,232	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**268,107**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)					
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS	4,000				
2. TRAVEL					
3. SUBSISTENCE	14,250				
4. OTHER	11,500				
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS				**29,750**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				72,814	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				3,000	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES				6,000	
5. SUBAWARDS					
6. OTHER				196,733	
TOTAL OTHER DIRECT COSTS				**278,547**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**576,404**	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE)	MTDC BASE: 374,921				
TOTAL INDIRECT COSTS (F&A)	RATE: 56.00%			**209,956**	
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)				**786,360**	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**786,360**	

M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT $			
PI/PD TYPED NAME & SIGNATURE*	DATE 4/15/18	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - ORG

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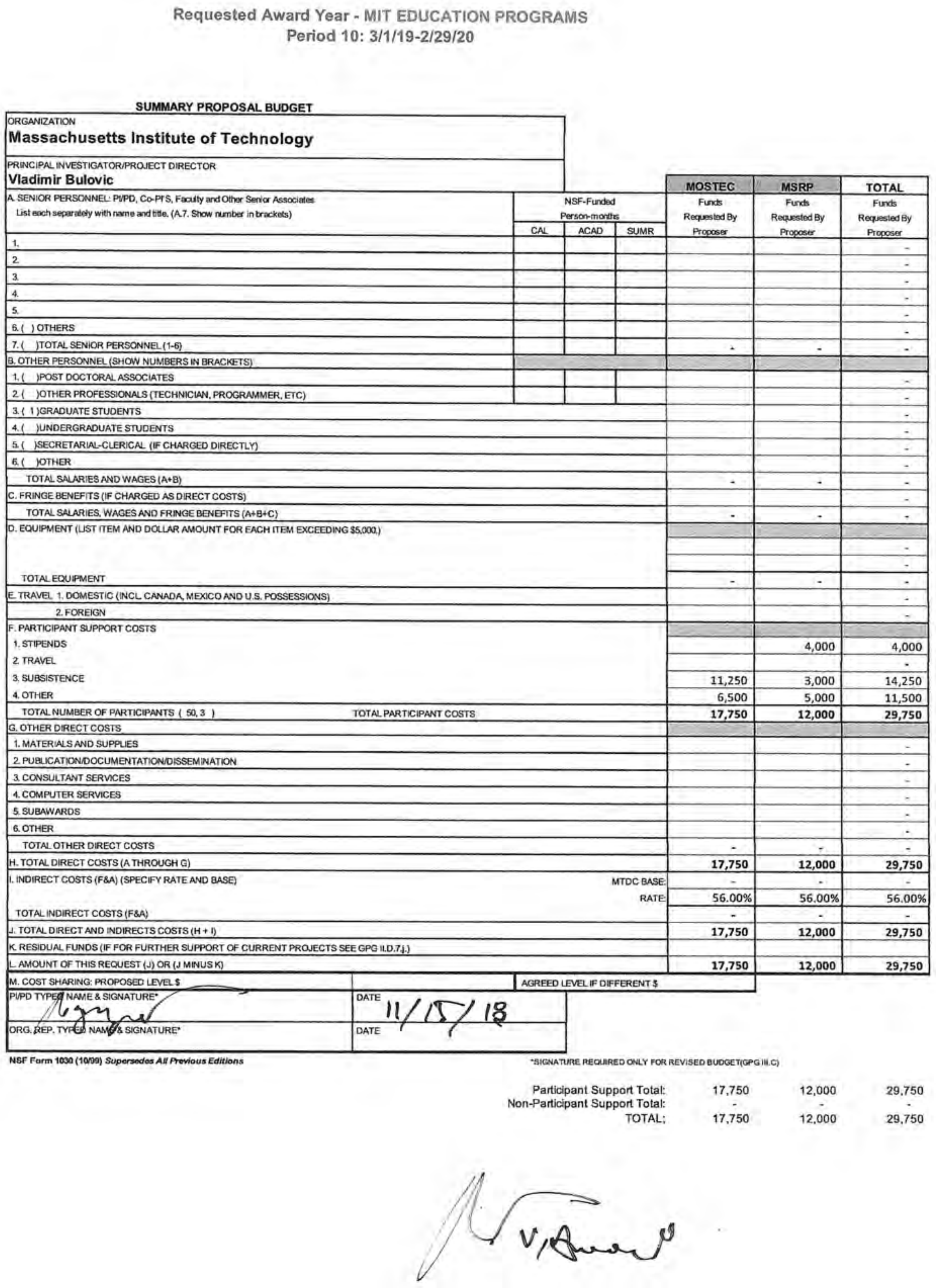

Requested Award Year - MIT EDUCATION PROGRAMS
Period 10: 3/1/19-2/29/20

SUMMARY PROPOSAL BUDGET

ORGANIZATION
Massachusetts Institute of Technology

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Vladimir Bulovic

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	**MOSTEC** Funds Requested By Proposer	**MSRP** Funds Requested By Proposer	**TOTAL** Funds Requested By Proposer
1.						-
2.						-
3.						-
4.						-
5.						-
6. ( ) OTHERS						-
7. ( )TOTAL SENIOR PERSONNEL (1-6)				-	-	-
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( )POST DOCTORAL ASSOCIATES						-
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)						-
3. (1)GRADUATE STUDENTS						-
4. ( )UNDERGRADUATE STUDENTS						-
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)						-
6. ( )OTHER						-
TOTAL SALARIES AND WAGES (A+B)				-	-	-
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)						-
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				-	-	-
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
						-
						-
TOTAL EQUIPMENT				-	-	-
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)						-
2. FOREIGN						-
F. PARTICIPANT SUPPORT COSTS						
1. STIPENDS					4,000	4,000
2. TRAVEL						-
3. SUBSISTENCE				11,250	3,000	14,250
4. OTHER				6,500	5,000	11,500
TOTAL NUMBER OF PARTICIPANTS (50, 3) TOTAL PARTICIPANT COSTS				**17,750**	**12,000**	**29,750**
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES						-
2. PUBLICATION/DOCUMENTATION/DISSEMINATION						-
3. CONSULTANT SERVICES						-
4. COMPUTER SERVICES						-
5. SUBAWARDS						-
6. OTHER						-
TOTAL OTHER DIRECT COSTS				-	-	-
H. TOTAL DIRECT COSTS (A THROUGH G)				**17,750**	**12,000**	**29,750**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:				-	-	-
RATE:				56.00%	56.00%	56.00%
TOTAL INDIRECT COSTS (F&A)				-	-	-
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)				**17,750**	**12,000**	**29,750**
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)						
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**17,750**	**12,000**	**29,750**

M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $
PI/PD TYPED NAME & SIGNATURE*	DATE 11/15/18	
ORG. REP. TYPED NAME & SIGNATURE*	DATE	

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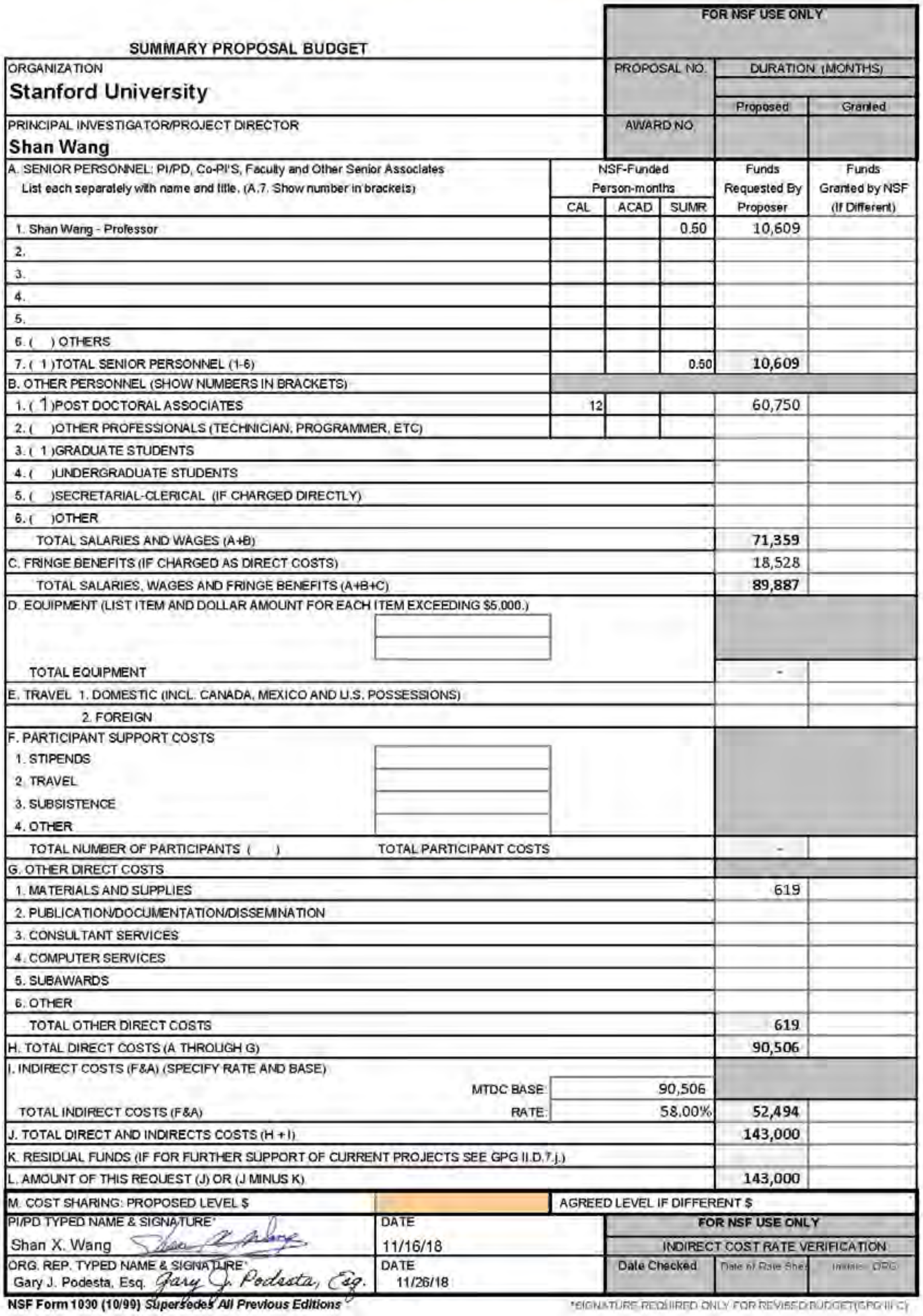
Participant Support Total:	17,750	12,000	29,750
Non-Participant Support Total:	-	-	-
TOTAL:	17,750	12,000	29,750

V, Bulovic

Requested Award Year
Period 10: 3/1/19-2/29/20



SUMMARY PROPOSAL BUDGET

ORGANIZATION **Stanford University**		PROPOSAL NO.	DURATION (MONTHS)	
			Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Shan Wang**		AWARD NO.		

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A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. Shan Wang - Professor			0.50	10,609	
2.					
3.					
4.					
5.					
6. ( ) OTHERS					
7. (1)TOTAL SENIOR PERSONNEL (1-6)			0.50	10,609	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1)POST DOCTORAL ASSOCIATES	12			60,750	
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)					
3. (1)GRADUATE STUDENTS					
4. ( )UNDERGRADUATE STUDENTS					
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6. ( )OTHER					
TOTAL SALARIES AND WAGES (A+B)				71,359	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				18,528	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				89,887	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)					
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS				-	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				619	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				619	
H. TOTAL DIRECT COSTS (A THROUGH G)				90,506	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE: 90,506 RATE: 58.00%					
TOTAL INDIRECT COSTS (F&A)				52,494	
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)				143,000	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				143,000	

M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $		
PI/PD TYPED NAME & SIGNATURE* Shan X. Wang Shan X. Wang	DATE 11/16/18	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Gary J. Podesta, Esq. Gary J. Podesta, Esq.	DATE 11/26/18	Date Checked	Date of Rate Sheet	Initials - ORG

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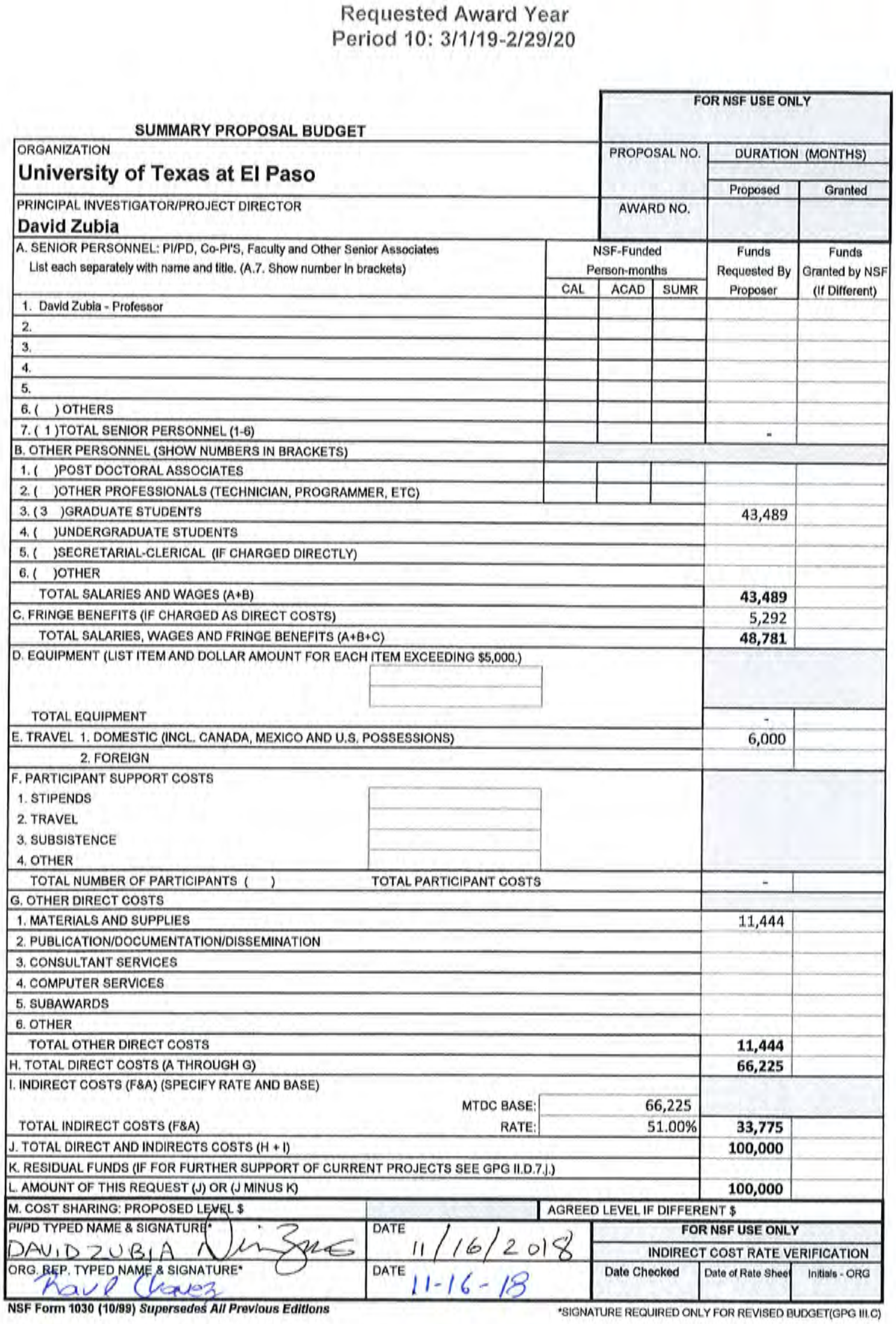

Requested Award Year
Period 10: 3/1/19-2/29/20

SUMMARY PROPOSAL BUDGET

FOR NSF USE ONLY

ORGANIZATION **University of Texas at El Paso**			PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **David Zubia**			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. David Zubia - Professor					
2.					
3.					
4.					
5.					
6. ( ) OTHERS					
7. (1)TOTAL SENIOR PERSONNEL (1-6)				-	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( )POST DOCTORAL ASSOCIATES					
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)					
3. (3)GRADUATE STUDENTS				43,489	
4. ( )UNDERGRADUATE STUDENTS					
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6. ( )OTHER					
TOTAL SALARIES AND WAGES (A+B)				**43,489**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,292	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**48,781**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				6,000	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS				-	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				11,444	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				**11,444**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**66,225**	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE: 66,225					
TOTAL INDIRECT COSTS (F&A) RATE: 51.00%				**33,775**	
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)				**100,000**	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**100,000**	

M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $		
PI/PD TYPED NAME & SIGNATURE* DAVID ZUBIA	DATE 11/16/2018	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Raul Chavez	DATE 11-16-18	Date Checked	Date of Rate Sheet	Initials - ORG

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Requested Award Year
Period 10: 3/1/19-2/29/20

SUMMARY PROPOSAL BUDGET

ORGANIZATION **Florida International University**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Sakhrat Khizroev**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
Sakhrat Khizreov		2%		3,201	10,974
2.					
3.					
4.					
5.					
6. ( ) OTHERS					
7. (1)TOTAL SENIOR PERSONNEL (1-6)		0.02		**3,201**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( )POST DOCTORAL ASSOCIATES					
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)					
3. ( )GRADUATE STUDENTS				27,600	
4. ( )UNDERGRADUATE STUDENTS					
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6. ( )OTHER					
TOTAL SALARIES AND WAGES (A+B)				**30,801**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,117	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**34,917**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				-	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				2,000	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS				-	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				8,018	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				500	
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER TUITION				9,119	
TOTAL OTHER DIRECT COSTS				**17,637**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**54,554**	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE: 45,435 RATE: 45.00%					
TOTAL INDIRECT COSTS (F&A)				**20,446**	
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)				**75,000**	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**75,000**	

M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $		
PI/PD TYPED NAME & SIGNATURE* Sakhrat Khizroev	DATE **11/16/2018**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Robert Gutierrez	DATE 11/16/2018	Date Checked	Date of Rate Shee	Initials - ORG

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4. *Center Support from All Sources*

The following table lists the annual levels of support for the Center for the current and for the requested award year. Table includes only funding that goes directly to, or is managed primarily by the Center.

	Current Award Year		Requested Award Year	
Award Source	Cash ($)	In-Kind	Cash ($)	In-Kind
NSF-STC Core funds	5,000,000		5,000,000	
Other NSF	68,700	156,355[1]	93,480	
Other Federal Agencies		34,000[2]		
State Government				
Local Government				
Industry	215,000			
University	80,170	108,680[3]	40,000	3,120
International		16,220[4]		
Private Foundations				
Other				
TOTAL	**5,363,870**	**315,255**	**5,133,480**	**3,120**

[1] NSF Graduate Research Fellowships
[2] NSDEG Graduate Fellowship
[3] UC Presidential Postdoc Fellowship; UC Berkeley Miller Postdoc Fellowship; UC Berkeley TTE-REU Tuition Waiver
[4] NSERC PGS-D Graduate Fellowship from Canada

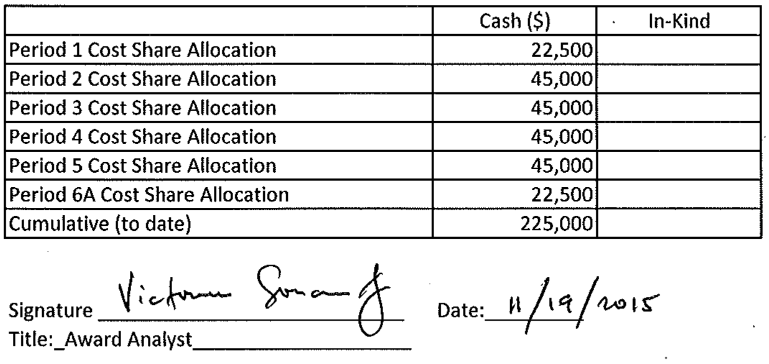
5. *Breakdown of Other NSF Funding*

	Current Award Year		Requested Award Year	
Funding Source	Cash ($)	In-Kind	Cash ($)	In-Kind
NSF Directorate for Engineering	38,700	22,188[1]	93,480	
NSF Office of Integrative Activities	30,000			
NSF Directorate for Mathematical & Physical Sciences		134,167[1]		
TOTAL	**68,700**	**156,355**[1]	**93,480**	

[1] NSF Graduate Research Fellowships

6. *Cost Sharing*

The following table documents, on an annual and cumulative basis, the amount of cost sharing for the Center. Effective Period 6B on September 1st, 2016, no new funds have been allocated for cost sharing.



	Cash ($)	In-Kind
Period 1 Cost Share Allocation	22,500	
Period 2 Cost Share Allocation	45,000	
Period 3 Cost Share Allocation	45,000	
Period 4 Cost Share Allocation	45,000	
Period 5 Cost Share Allocation	45,000	
Period 6A Cost Share Allocation	22,500	
Cumulative (to date)	225,000	

Signature Victoria

Title:_Award Analyst

Date: 11/19/2015

7. *Additional PI Support from All Sources*

The following table lists additional annual levels of support, not included in Section 4 above, awarded to Center PIs for the current award year and for the requested award year.

	Current Award Year		Requested Award Year	
Award Source	Cash ($)	In-Kind	Cash ($)	In-Kind
NSF	3,958,877	28,000	2,593,851	28,000
Other Federal Agencies	7,011,859	-	13,974,269	-
State Government	-	-	-	-
Local Government	-	-	-	-
Industry	7,189,469	-	2,477,386	-
University	870,285	-	379,431	-
International	1,065,000	-	1,288,000	-
Private Foundations	-	-	-	-
Other	1,010,043	-	904,041	-
TOTAL	**21,105,533**	**28,000**	**21,616,978**	**28,000**

XI. REFERENCES CITED

[1] A. C. Seabaugh and Q. Zhang, "Low-Voltage Tunnel Transistors for Beyond CMOS Logic," *Proceedings of the IEEE*, vol. 98, pp. 2095-2110, 2010.

[2] Z. Xin, A. Vardi, and J. A. del Alamo, "InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs Fabricated by a Top-Down Approach," *IEEE International Electron Devices Meeting (IEDM)*, pp. 25.5.1-4, 2014.

[3] T. Xiao, X. Zhao, S. Agarwal, and E. Yablonovitch, "Impact of Interface Defects on Tunneling FET Turn-on Steepness," presented at the *Fourth Berkeley Symposium on Energy Efficient Electronic Systems, Berkeley, CA, USA*, 2015.

[4] G. Dewey, B. Chu-Kung, J. Boardman, J. M. Fastenau, J. Kavalieros, R. Kotlyar, et al., "Fabrication, Characterization, and Physics of III–V Heterojunction Tunneling Field Effect Transistors (H-TFET) for Steep Sub-Threshold Swing," in *Electron Devices Meeting (IEDM) IEEE International, Washington, DC,* pp. 33.6.1 - 33.6.4., 2011.

[5] D. Sarkar, X. Xie, W. Liu, W. Cao, J. Kang, Y. Gong, et al., "A Subthermionic Tunnel Field-Effect Transistor with an Atomically Thin Channel," *Nature*, vol. 526, pp. 91-95, 2015.

[6] R. Gandhi, Z. Chen, N. Singh, K. Banerjee, and S. Lee, "Vertical Si-Nanowire n-Type Tunneling FETs With Low Subthreshold Swing (<= 50 mV/decade) at Room Temperature," *IEEE Electron Device Letters*, vol. 32, pp. 437-439, 2011.

[7] K. Jeon, W. Y. Loh, P. Patel, C. Y. Kang, J. Oh, A. Bowonder, et al., "Si Tunnel Transistors with a Novel Silicided Source and 46mV/dec Swing," *2010 Symposium on VLSI Technology, Digest of Technical Papers*, pp. 121-122, 2010.

[8] H. Kam, V. Pott, R. Nathanael, J. Jeon, E. Alon, and T. J. King Liu, “Design and reliability of a micro-relay technology for zero-standby-power digital logic applications,” *IEEE IEDM Tech. Dig*., pp. 809-811, 2009.

[9] F. Niroui, A. I. Wang, E. M. Sletten, Y. Song, J. Kong, E. Yablonovitch, et al., "Tunneling Nanoelectromechanical Switches Based on Compressible Molecular Thin Films," *ACS Nano*, vol. 9, pp. 7886-7894, 2015.

[10] K. Settaluri, C. Lalau-Keraly, E. Yablonovitch, and V. Stojanović, “First Principles Optimization of Opto-Electronic Communication Links,” *IEEE Transactions on Circuits and Systems I: Regular Papers* , vol.64, no.5, pp. 1270-1283, May 2017.

[11] E. K. Lau, A. Lakhani, R. S. Tucker, and M. C. Wu, "Enhanced Modulation Bandwidth of Nanocavity Light Emitting Devices," *Optics Express*, vol. 17, pp. 7790–7799, 2009.

[12] D. Miller, “Device requirements for optical interconnects to CMOS silicon chips,” *Proc. IEEE*, vol. 97, pp. 1166–1185, 2009.

[13] D. Bhowmik, L. You, S. Salahuddin, and Ieee, "Possible Route to Low Current, High Speed, Dynamic Switching in a Perpendicular Anisotropy CoFeB-MgO Junction Using Spin Hall Effect of Ta," *IEEE International Electron Devices Meeting (IEDM)*, pp. 29.7.1-29.7.4, 2012.

[14] Y. Yang, R. Wilson, J. Gorchon, C.-H. Lambert, S. Salahuddin and J. Bokor, “Ultrafast Magnetization Reversal by Picosecond Electrical Pulses,” *Science Advances*, vol. 3, no. 11, pp. E1603117 Nov 2017.

[15] W. Lu, X. Zhao, D. Choi, S. El Kazzi and J. A. del Alamo, “Alcohol-Based Digital Etch for III-V Vertical Nanowires Sub-10 nm Diameter,” *IEEE Electron Device Lett.*, vol. 38, no. 5, pp. 548-551, May 2017.

[16] X. Zhao, A. Vardi and J. A. del Alamo, “Sub-Thermal Subthreshold Characteristics in Top-down InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs,” *IEEE Electron Device Lett.*, vol. 38, no. 7, pp. 855-858, Jul 2017.

[17] Zhao, X., C. Heidelberger, E. A. Fitzgerald, W. Lu and J. A. del Alamo, “Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs.” *IEEE International Electron Devices Meeting*, San Francisco, CA, pp. 413-416, December 2-6, 2017.

[18] Zhao, X., C. Heidelberger, E. A. Fitzgerald, W. Lu, A. Vardi and J. A. del Alamo, “Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs: Ni vs. Mo Contacts.” *IEEE Transactions on Electron Devices*, Vol. 65, No. 9, pp. 3762-3768, September 2018.

[19] Lu, W., Y. Lee, J. Murdzek, J. Gertsch, A. Vardi, L. Kong, S. M. George and J. A. del Alamo, “First Transistor Demonstration of Thermal Atomic Layer Etching: InGaAs FinFETs with sub-5 nm Fin-width Featuring in-situ ALE-ALD.” *IEEE International Electron Devices Meeting*, San Francisco, CA, December 1-5, 2018.

[20] W. S. Leong, Q. Ji, N. Mao, Y. Han, H. Wang, A. J. Goodman, C. Su, Y. Guo, P.-C. Shen, Z. Gao, D. A. Muller, W. A. Tisdale and J. Kong, “Synthetic Lateral Metal-Semiconductor Heterostructures of Transition Metal Disulfides,” *J. Am. Chem. Soc.*, vol. 140, pp. 12354–12358, Sep 2018.

[21] D. J. Rizzo, G. Veber, T. Cao, C. Bronner, T. Chen, F. Zhao, H. Rodriguez, S. G. Louie, M. F. Crommie and F. R. Fischer, “Topological band engineering of graphene nanoribbons,” *Nature*, vol. 560, pp. 204-208, Aug 2018.

[22] T. Cao, F. Zhao, and S. G. Louie, “Topological Phases in Graphene Nanoribbons: Junction States, Spin Centers, and Quantum Spin Chains,” *Physical Review Letters*, vol.119, no. 7-18, pp. 076401, Aug 2017.

[23] Y.-H. Yoon, Y. Jin, C.-K. Kim, S. Hong, J.-B. Yoon, “A Low Contact Resistance 4-Terminal Mems Relay: Theoretical Analysis, Design, and Demonstration,” *Journal of MicroElectroMechanical Systems*, vol. 27, no. 3, pp. 497-505, 2018.

[24] Z. A. Ye, S. Almeida, M. Rusch, A. Perlas, W. Zhang, U. Sikder, J. Jeon, V. Stojanović and T.-J. K. Liu, “Demonstration of Sub-50 mV digital integrated circuits with microelectromechnical relays,” *IEEE International Electron Devices Meeting*, San Francisco, CA, Dec 2018.

[25] F. Chen, H. Kam, D. Marković, T.-J. K. Liu, V. Stojanović and E. Alon, "Integrated circuit design with NEM relays," *2008 IEEE/ACM International Conference on Computer-Aided Design*, pp. 750-757, 2008.

[26] S. A. Fortuna, C. Heidelberger, K. Messer, K. Han, E.A. Fitzgerald, E. Yablonovitch, and M.C. Wu, “Optical Antenna Enhanced Spontaneous Emission Rate in Electrically Injected Nanoscale III-V LED,” *International Semiconductor Laser Conference*, May 2016.

[27] S. A. Fortuna, A. Taghizadeh, E. Yablonovitch, and M. C. Wu, “Toward 100 GHz Direct Modulation Rate of Antenna Coupled NanoLED,” *IEEE Photonics Conference*, Jan 2016

[28] K. Han, S. Fortuna, M. Amani, S. Desai, D.-H. Lien, G. H. Ahn, E. Yablonovitch, A. Javey and M. C. Wu, “Bright Electroluminescence from Back-Gated WSe2 P-N Junctions Using Pulsed Injection,” *CLEO*, May 2018.

[29] F. Withers, *et al*., “WSe2 Light-Emitting Tunneling Transistors with Enhanced Brightness at Room Temperature,” *Nano Lett.*, vol. 15, pp. 8223–8228, 2015.

[30] B. W. H. Baugher, H. O. H. Churchill, Y. Yang, and P. Jarillo-Herrero, “Optoelectronic devices based on electrically tunable p-n diodes in a monolayer dichalcogenide,” *Nat. Nanotechnol.*, vol. 9, pp. 262–267, 2014.

[31] J. Hong, P. Liang, V. Safonov, and S. Khizroev, “Energy-efficient spin-transfer-torque based sub-10-nm magnetic tunneling junctions,” *J. Nanoparticle Research*, vol. 15, pp. 1599, 2013.

[32] K. Y. Camsari, S. Salahuddin, and S. Datta, “Implementing p-bits With Embedded MTJ,” *IEEE Electron Device Letters*, vol. 38, pp. 1767-1770, Dec 2017.

[33] "International Technology Roadmap for Semiconductors," 2007.

[34] C. H. Bennett, "The Thermodynamics if Computation - a Review," *International Journal of Theoretical Physics*, vol. 21, pp. 905-940, 1982.

[35] R. Landauer, "Irreversibility and Heat Generation in the Computing Process," *IBM Journal of Research and Development*, vol. 5, pp. 183-191, 1961.

[36] C. H. Bennett, "Logical Reversibility of Computation," *IBM Journal of Research and Development*, vol. 17, pp. 525-532, 1973.

[37] R. R. Razouk and B. E. Deal, "Dependence of Interface State Density on Silicon Thermal-Oxidation Process Variables," *Journal of the Electrochemical Society*, vol. 126, pp. 1573-1581, 1979.

[38] T. Roy, M. Tosun, X. Cao, H. Fang, D.-H. Lien, P. Zhao, Y.-Z. Chen, Y.-L. Chueh, J. Guo, and A. Javey, “Dual-Gated MoS_2/WSe_2 van der Waals Tunnel Diodes and Transistors,” *ACS Nano*, vol. 9, pp. 2071-2079, Feb 2015.

[39] Z. Gao, Q. Ji, P.-C. Shen, Y. Han, W. S. Leong, N. Mao, L. Zhou, C. Su, J. Niu, X. Ji, M. M. Goulamaly, D. A. Muller, Y. Li and J. Kong, “In-situ Generated Volatile Precursor for CVD Growth of a Semimetallic 2D Dichalcogenide,” *ACS Appl. Mater. Interfaces*, vol. 10, pp. 34401–34408, Sep 2018.

[40] A. Amani, D.-H. Lien, D. Kiriya, J. Xiao, A. Azcatl, J. Noh, et al., "Near-Unity Photoluminescence Quantum Yield in MoS2," *Science*, vol. 350, pp. 1065-1068, 2015.

[41] M. Amani, R. A. Burke, X. Ji, P. Zhao, D.-H. Lien, P. Taheri, G. H. Ahn, D. Kiriya, J. W. Ager, E. Yablonovitch, J. Kong, M. Dubey, and A. Javey, “High Luminescence Efficiency in MoS2 Grown by Chemical Vapor Deposition,” *ACS Nano*., vol. 10, no.7, pp. 6535 -6541, Jun 2016.

[42] P. Zhao, M. Amani, G. Ahn, D.-H. Lien, D. Kiriya, J. Mastandrea, J. Ager III, E. Yablonovitch, D. Chrzan and A. Javey, “Measuring the Edge Recombination Velocity of Monolayer Semiconductors,” *Nano Letters*, vol. 17, no. 9, pp. 5356–5360, Aug 2017.

[43] Y.-L. Lee, F. Zhao, T. Cao, J. Ihm and S. G. Louie, “Topological phases in cove-edged and chevron graphene nanoribbons: Geometric structures, Z2 invariants, and junction states,” *Nano Lett.*, vol. 18, pp. 7247-7253, Sep 2018.

[44] F. Chen, H. Kam, D. Markovic, T. J. King Liu, V. Stojanovic, E. Alon, “Integrated circuit design with NEM relays,” *Proc. IEEE/ACM ICCAD*, pp. 750-757, 2008.

[45] F. Niroui, J. Patil, T. Swager. J. Lang, and V. Bulovic, “Towards Low-Stiction Nanoelectromechanical Switches Using Self-Assembled Molecules,” *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.

[46] W. S. Yun, S. W. Han, S. C. Hong, I. G. Kim, and J. D. Lee, "Thickness and strain effects on electronic structures of transition metal dichalcogenides: 2H-M X 2 semiconductors (M= Mo, W; X= S, Se, Te)," *Physical Review B*, vol. 85, no. 3, p. 033305, 2012.

[47] S.A. Fortuna, M.S. Eggleston, K. Messer, E. Yablonovitch, and M. C. Wu, “Large Spontaneous Emission Rate Enhancement from an Electrically-injected nanoLED Coupled to an Optical Antenna,” *IPC*, Oct 2015.

[48] Y. Kim, S. S. Cruz, K. Lee, B. O. Alawode, C. Choi, Y. Song, J. M. Johnson, C. Heidelberger, W. Kong, S. Choi, K. Qiao, E. A. Fitzgerald, J. Kong, A. M. Kolpak, J. Hwang, and J. Kim, “Remote epitaxy through graphene: Role of underlying substrates on van der Waals epitaxy,” *Nature*, vol. 544, pp. 340–343, 2017.

[49] M. Eggleston, K. Messer, L. Zhang, E. Yablonovitch, and M. C. Wu, “Optical Antenna Enhanced Spontaneous Emission,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 112, pp. 1704–1709, Feb 2015.

[50] K. Han, M. Amani, G.H. Ahn, K. Yu, E. Yablonovitch, A. Javey, and M. C. Wu, “WSe2 light-emitting diode coupled to optical bowtie antennas,” *21st Microoptics Conference*, Oct 2016.

[51] K. Han, S. Fortuna, M. Amani, S. Desai, E. Yablonovitch, A. Javey, and M. Wu, “TMDC Based nanoLEDs for High-Speed Energy-Efficient Optical Interconnects,” 5th *Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop*, Berkeley, CA, October 2017.

[52] R. Wilson, J. Gorchon, Y. Yang, C-H. Lambert, S. Salahuddin, and J. Bokor., “Ultrafast magnetic switching of GdFeCo with electronic heat currents,” *Physical Review B*, vol. *95*, no. 18 pp.180409 May 2017.

[53] R.B. Wilson, Y. Yang, J. Gorchon, C.-H. Lambert, S. Salahuddin, and J. Bokor, “Electric current induced ultrafast demagnetization,” *Physical Review B*, vol. 96, no. 4, pp. 045105 Jul 2017.

[54] I. Radu, K. Vahaplar, C. Stamm, T. Kachel, N. Pontius, et al., “Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins,“ *Nature*, vol. 472, pp. 205-208, 2011.

[55] J. Gorchon, C.-H. Lambert, Y. Yang, A. Pattabi, R. B. Wilson, S. Salahuddin, and J. Bokor, “Single shot ultrafast all optical magnetization switching of ferromagnetic Co/Pt multilayers,” *Appl. Phys. Lett*., vol.111, pp. 042401, Jul 2017

[56] J. Hong, M. Stone, B. Navarette, K. Luongo, Z. Yuan, K. Xia, N. Xu, J. Bokor, L. You and S. Khizroev, “3D multilevel spin transfer toque devices,” *Appl. Phys. Lett.*, vol. 112, pp. 112402, Mar 2018.

[57] J. Butler, M. Shachar, B. Lee, D. Garcia, B. Hu, J. Hong, N. Amos, and S. Khizroev, “Reconfigurable and non-volatile vertical magnetic logic gates,” *Journal of Applied Physics*, vol. 115, pp. 163903, 2014.

[58] J. Hong, A. Hadjikhani, M. Stone, P. Liang, F. Allen, V. Safonov, J. Bokor, and S. Khizroev, “The Physics of Spin-transfer Torque Switching in Magnetic Tunneling Junctions in Sub-10-nm Size Range,” *IEEE Transactions on Magnetics*, vol. 52, no. 7, Jul 2016.

XII. APPENDICES

Appendix A: Biographical Information of New Faculty Members

New Faculty in Period 9:

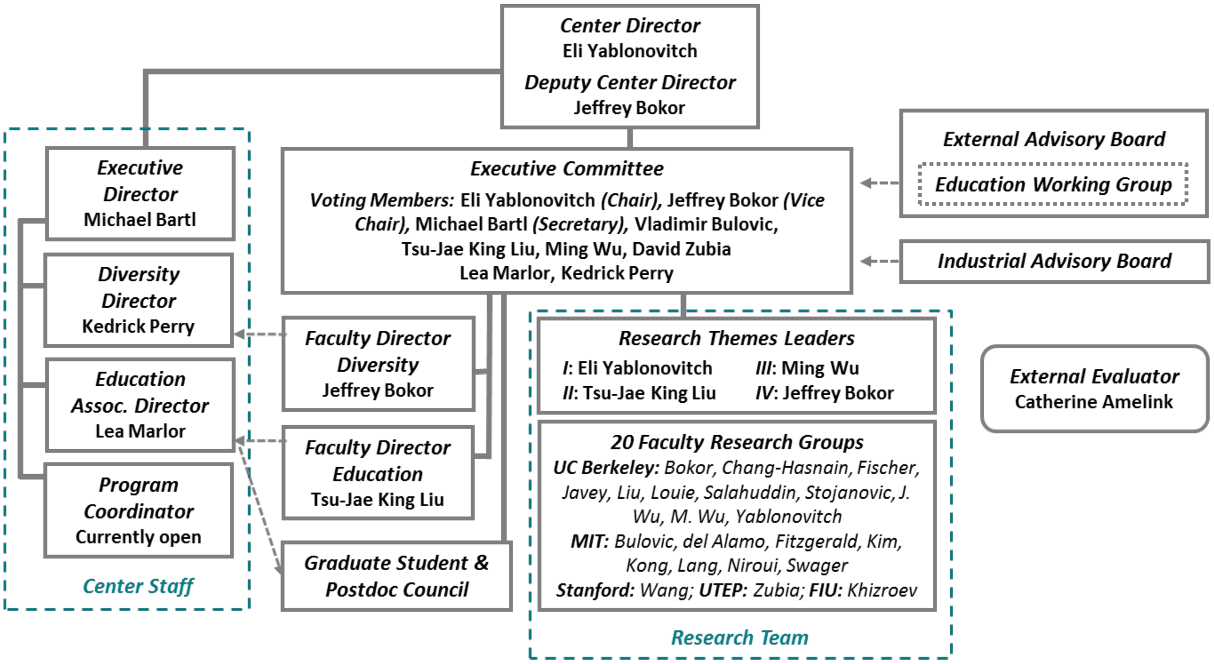
Shan Xian Wang is a professor of materials science & engineering, and jointly a professor of electrical engineering at Stanford University. His research interests lie in nanotechnology and information storage, magnetic nanoparticles, nano-patterning, spin electronic materials and sensors, as well as magnetic integrated inductors and transformers. He has over 250 publications, and holds 56 patents (issued and pending), and is an author of the textbook entitled "Magnetic Information Storage Technology".

Jeehwan Kim is an associate professor at the Massachusetts Institute of Technology in mechanical engineering and materials science and engineering. He is a principal investigator in Research Laboratory of Electronics at MIT. His group focuses on innovations in nanotechnology for next generation computing and electronics. Before joining MIT in 2015, he was a research staff member at IBM T.J. Watson Research Center in Yorktown Heights, NY since 2008. Many of his patents have been licensed for commercialization. He is a recipient of 20 IBM high value invention achievement awards. In 2012, he was appointed a "Master Inventor" of IBM in recognition of his active intellectual property generation and commercialization of his research. He is an inventor of 200 issued/pending US patents and an author of 40 articles in journals including multiple *Science, Nature, and Nature Materials*. He received his B.S. from Hongik University, his M.S. from Seoul National University, and his Ph.D. from UCLA in 2008, all of them in materials science.

Farnaz Niroui is an assistant professor of electrical engineering and computer science at the Massachusetts Institute of Technology. Her research interest lies at the interface of device physics, nanofabrication, and materials science to study, manipulate and engineer devices and systems with unique functionalities at the nanoscale. Before starting her faculty position, she was a Miller postdoctoral fellow at the University of California, Berkeley. She received her PhD and master's degrees in electrical engineering from MIT and her bachelor's degree in nanotechnology engineering from the University of Waterloo.

Appendix B: Organizational Chart

Center for Energy Efficient Electronics Science (E^3S)
November 30, 2018



Center Director
Eli Yablonovitch
Deputy Center Director
Jeffrey Bokor

Executive Committee
Voting Members: Eli Yablonovitch *(Chair)*, Jeffrey Bokor *(Vice Chair)*, Michael Bartl *(Secretary)*, Vladimir Bulovic, Tsu-Jae King Liu, Ming Wu, David Zubia Lea Marlor, Kedrick Perry

External Advisory Board
Education Working Group

Industrial Advisory Board

Executive Director
Michael Bartl

Diversity Director
Kedrick Perry

Education Assoc. Director
Lea Marlor

Program Coordinator
Currently open

Center Staff

Faculty Director Diversity
Jeffrey Bokor

Faculty Director Education
Tsu-Jae King Liu

Graduate Student & Postdoc Council

Research Themes Leaders
I: Eli Yablonovitch
II: Tsu-Jae King Liu
III: Ming Wu
IV: Jeffrey Bokor

20 Faculty Research Groups
UC Berkeley: *Bokor, Chang-Hasnain, Fischer, Javey, Liu, Louie, Salahuddin, Stojanovic, J. Wu, M. Wu, Yablonovitch*
MIT: *Bulovic, del Alamo, Fitzgerald, Kim, Kong, Lang, Niroui, Swager*
Stanford: *Wang;* ***UTEP:*** *Zubia;* ***FIU:*** *Khizroev*

Research Team

External Evaluator
Catherine Amelink

Appendix C: 2018 External Advisory Board Meeting Agenda

Center for Energy Efficient Electronics Science
2018 External Advisory Board Meeting

October 17, 2018
Sutardja Dai Hall, 6th Floor, Room 630
University of California, Berkeley

ADVANCE AGENDA

8:00 AM		*Breakfast & Check-In*	
8:30 AM	0:10	**Welcome, Review of Agenda**	**Eli Yablonovitch**
8:40 AM	0:35	**Center Overview**	**Eli Yablonovitch**
9:15 AM		**Education & Diversity**	
	0:45	Overview Presentations	**Lea Marlor, Kedrick Perry**
	0:15	Q&A	
10:15 AM	0:15	*Break*	
10:30 AM		**Theme I: Nanoelectronics**	
	0:30	Research Presentations	**Eli Yablonovitch, Sri Krishna Vadlamani**
	0:15	Q&A	
11:15 PM		**Theme II: Nanomechanics**	
	0:30	Research Presentations	**Tsu-Jae King Liu, Zhixin Alice Ye**
	0:15	Q&A	
12:00 PM	1:00	**Lunch & Poster Session**	
1:00 PM	0:25	**Center Management & Knowledge Transfer**	**Michael Bartl**
1:25 PM		**Theme III: Nanophotonics**	
	0:30	Research Presentations	**Ming Wu, Seth Fortuna**
	0:15	Q&A	
2:10 PM	0:15	*Break*	
2:25 PM		**Theme IV: Nanomagnetics**	
	0:30	Research Presentations	**Jeffrey Bokor, Amal El-Ghazaly**
	0:15	Q&A	
3:10 PM		**System Integration**	
	0:20	Research Presentation	**Vladimir Stojanović, Rawan Naous**
	0:10	Q&A	
3:40 PM	0:10	**Wrap-Up and Closing Remarks**	**Eli Yablonovitch**
3:50 PM	0:10	*Break*	
4:00 PM	1:00	**EAB Deliberations**	
5:00 PM		**Critical Feedback to E^{3}S and Dinner**	

2018 EAB Meeting Advance Agenda

Appendix D: 2018 Research Seminar Attendance

Dates	**Faculty**	**Postdocs**	**Graduate Students**	**Undergrad Students**	**Staff**	**Other**
2018 Seminar Series						
February 2	4	7	21	0	5	0
February 9	3	7	18	0	5	0
February 14	3	7	12	0	3	0
February 16	7	7	15	0	4	0
April 6	7	8	16	1	4	0
September 14	8	10	20	1	3	0
September 28	7	5	15	1	3	1
October 5	6	7	12	0	1	3

Appendix E: E^{3}S Professional Development Program

E^{3}S Professional Development Program

Objective: Equip E^{3}S students and postdoctoral researchers with the skills and experiences needed to maximize their potential and success in their professional careers.

Certificate Requirements: Formal, but flexible requirements
- At least one training in leadership, teaching **OR** mentoring
- Three other areas required

Training Areas: Leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship

Training Opportunities: Workshops and hands-on experience in training areas

Leadership*
- Complete online or in-person leadership training (1 hour)
- Complete diversity training (1 hour)
- Take lead in 1 leadership event *OR* supporting role in 3 events
- Opportunities: Graduate Student Postdoc Council, seminar coordinator, journal club coordinator, retreat committee, STC Directors Meeting, E^{3}S representative, theme meeting coordinator, REU selection committee, poster session evaluator

Teaching*
- Complete online or in-person teacher training (1 hour)
- Complete diversity training (1 hour)
- Practice teaching *OR* develop course curriculum at any academic level of your choice
- Opportunities: Curriculum development for outreach programs, E^{3}S summer school, online course development, MOSTEC instructor

Mentoring*
- Attend mentor training (1 hour)
- Complete diversity training (1 hour)
- Mentor an undergraduate or high school student
- Opportunities: E^{3}S REU, ETERN, TTE REU, MOSTEC, RET

Outreach
- Attend outreach training (1 hour)
- Take lead in 1 outreach event or supporting role in 3 events
- Opportunities: Research presentation for non-scientists & engineers, lead hands on project for high school students, Cal-Day, EECS Visit, Berkeley EDGE

Conference, serve as judge at science fair, demonstrate research at science fair for k-12 students, laboratory tour

Science Communication

- Attend a science communication workshop (1 hour)
- Present research to center (1 hour)
- Present research to non-center audience (1 hour)
- Opportunities: Poster presented at annual retreat, EAB, Site Visit, or E^{3}S Symposium; presentation at annual retreat, EAB, Site Visit, Journal Club, Research seminar, or E^{3}S Symposium

Proposal Writing

- Attend a proposal writing workshop (1 hour)
- Write and submit proposal on research, education, and diversity activities
- Opportunities: proposal for E^{3}S education, diversity or research programs

Entrepreneurship

- Attend an entrepreneurship workshop (1 hour)
- Develop and submit a business plan *OR* complete innovation and commercialization course

**Leadership, teaching, and mentoring training areas include additional training on diversity.*

Student Name:

____

Professional Development Opportunities

LEADERSHIP	
______	Graduate Student & Postdoc Council: Organize one meeting per term to discuss E3S students/postdocs activities, events, concerns (fall & spring/1-3 hours)
______	Research Teleseminar Coordinator: Contact speakers and set up videoconference (fall & spring/bi-weekly)
______	Journal Club Coordinator: Contact speakers and set up videoconference (summer/bi-weekly)
______	Retreat Planning Committee: Help plan and host student/postdoc retreat (August/5-10 hours)
______	Spring Research Review Committee: Help plan and host 1-day spring conference for E3S students/postdocs (Spring/5-10 hours)
______	STC Directors Meeting: Serve as E3S students/postdocs student representative and participate in poster session (August or September/1-2 days)
______	Institution Representative: Serve as point of contact to welcome new students/postdocs to center at your institution and relay student concerns to the student council and to bring up to the executive committee (1-year term)
TEACHING & CURRICULUM DEVELOPMENT	
______	E3S Summer Research Workshop (E3S SRW): Instruct one-week course on introduction to electronics (1 week in summer/40 hours)
______	Curriculum Development: Create tradition and online course modules for in energy efficient electronics topics for teachers and high school students (10-20 hours)
MENTORING	
______	E3S Research Experience for Undergraduates (E3S REU): Mentor undergraduate students during summer (9-week internship/40 hours per week)

______	E3S Internship (ETERN): Mentor undergraduate students during fall/spring terms (10-week internship/10 hours per week)
______	MIT Online Science Technology Engineering Community (MOSTEC): Mentor high school students online. Provide information about being a scientist of engineer, discuss how to apply to college, provide guidance on research project (August – January/1-3 hours per week)
EVALUATION	
______	REU Poster Evaluator: Review poster at summer research program end-of-year poster symposium (1 day/2 hours)
______	REU Application Evaluator: Review applications for summer research programs (5-10 hours)
RESEARCH (Posters)	
______	Site Visit Poster Session: Present your research at NSF Site Visit (1-2 days: January 12-13, 2017)
______	BEARS Poster Session (UC Berkeley only): Present your research to industrial partners and potential donors (February 2017/2 hours)
______	Graduate Student Visit Day – Poster Session: Present your research to admitted graduate students (March 2017/2 hours)
RESEARCH (Presentations)	
______	Present at research seminar (fall or spring /1 hour)
______	Present at journal club (summer /1 hour)
RESEARCH (Tours)	
______	Cleanroom tour
______	Lab tour
______	Other, please specify: ___________________________________
OUTREACH	
______	Research presentation for non-scientists & engineers (e.g., teachers, middle and high school students (1 day/1-2 hours)
______	Lead hands-on project for high school students (1 day/2 hours)
______	Serve as judge at science fair (1 day/2-4 hours)

_____	Demonstrate research at science fair for middle and high school students (1 day/2-4 hours)
_____	Panel member: Talk about experience as scientist or engineer (1 day/1-2 hours)
_____	Present to summer research students on career development topics (e.g., creating posters, giving technical talks, applying for fellowships, writing scientific papers, applying to graduate school, etc.) (1 day/1-2 hours) Please specify topic(s) of interest: __________________________
OTHER *(must be approved by Education and Outreach Director)*	
_____	Please specify:
_____	Please specify:

Appendix F: E^{3}S REU Recruitment Calendar

2018 Joint Recruitment Calendar

for Summer Research Experiences for Undergraduates and Engineering Graduate Diversity

February 2018			
National Society of Black Engineers (NSBE)	March 21-March 25	Pittsburgh, PA	E3S
October 2018			
Grace Hopper	October 4-6	Orlando, FL	UCB
AISES	October 4-6	Oklahoma City, OK	UCB
Society for the Advancement of Chicanos and Native Americans in Science (SACNAS)	October 11-13	San Antonio, TX	E3S
Society of Women Engineers (SWE)	October 18-20	Minneapolis, MN	UCB
November 2018			
Society of Hispanic Professional Engineers (SHPE)	November 9-10	Cleveland, OH	E3S
OSTEM	November 15-18	Houston, TX	UCB

Appendix G: TTE REU Recruitment Calendar

Ohlone College	November 30	Fremont, CA
College of the Canyons	December 5	Santa Clarita, CA
Los Angeles Trade Technical College	December 5	Los Angeles, CA
Pasadena City College	December 6	Pasadena, CA
Rio Hondo College	December 7	Whittier, CA
TTE Webinars	November 7, November 13, November 30, December 3, January 18, and January 24	Online

Appendix H: 2018 STC Directors Meeting

2018 STC DIRECTORS MEETING: PROGRAM SCHEDULE

TUESDAY, AUGUST 21, 2018

7:15 am		**Registration & Breakfast**
8:00 am		**Welcome Remarks**
		Tsu-Jae King Liu, Dean, College of Engineering, UC Berkeley
		Eli Yablonovitch, Director, Center for E3S, UC Berkeley
		Michael Bartl, Executive Director, Center for E3S, UC Berkeley
8:20 am		**Informal Science Communication**
	8:20 am	**Caleb Cheung**, Chabot Space & Science Center, Oakland *"Bringing science closer to the public through children and youth"*
	8:45 am	Questions & Discussion
	8:55 am	**Carol Lynn Alpert**, Museum of Science, Boston *"Science communication skills that advance discovery and innovation"*
	9:20 am	Questions & Discussion
	9:30 am	**Jennifer Frazier**, Exploratorium, San Francisco *"Seeing the unseen: Engaging the public in new areas of research through visualizations"*
	9:55 am	Questions & Discussion
10:00 am		**Break**
10:20 am		***Panel: Bringing Science and Engineering to the Public***
		Roseanne Ford, Moderator (Chemical Engineering, University of Virginia)
		Panelists: **Caleb Cheung** (Chabot Space & Science Center, Oakland), **Carol Lynn Alpert** (Museum of Science, Boston), **Jennifer Frazier** (Exploratorium, San Francisco), **Seth Shostak** (SETI Institute, Mountain View), **Kedrick Perry** (Center for E3S, UC Berkeley)
11:10 am		***STC Presentations (Class of 2013)***
	11:15 am	**Edward Snell**, SUNY Buffalo *Center for Biology with X-Ray Free Electron Lasers (BioXFel)*
	11:30 am	Questions & Discussion
	11:35 am	**Kenneth Blum**, Harvard University *Center for Brains, Minds, and Machines (CBMM)*
	11:50 am	Questions & Discussion
	11:55 am	**Robert Westervelt**, Harvard University *Center for Integrated Quantum Materials (CIQM)*
	12:10 pm	Questions & Discussion
12:15 pm		**Lunch**

2018 STC DIRECTORS MEETING: PROGRAM SCHEDULE

1:15 pm		***Science Journalism: Are We Preaching to the Choir?***
	1:15 pm	**Peter Aldhous**, BuzzFeed News, San Francisco *"Science reporters: Cheerleaders or watchdogs?"*
	1:40 pm	Questions & Discussion
	1:50 pm	**Erika Check Hayden**, Science Communication Program, UC Santa Cruz *"Communicating to close the gap between scientists and the public"*
	2:15 pm	Questions & Discussion
	2:25 pm	**Nsikan Akpan**, PBS NewsHour, Washington, DC *"PLEASE WATCH! Video storytelling for science news"*
	2:50 pm	Questions & Discussion
	3:00 pm	**Seth Shostak**, SETI Institute, Mountain View *"Is telling people how science works a lost cause?"*
	3:25 pm	Questions & Discussion
3:30 pm		**Break**
3:45 pm		***STC Presentations (Class of 2016)***
	3:50 pm	**Ritchie Patterson**, Cornell University *Center for Bright Beams (CBB)*
	4:05 pm	Questions & Discussion
	4:10 pm	**Wallace Marshall**, UC San Francisco *Center for Cellular Construction (CCC)*
	4:25 pm	Questions & Discussion
	4:30 pm	**Vivek Shenoy**, University of Pennsylvania *Center for Engineering MechanoBiology (CEMB)*
	4:45 pm	Questions & Discussion
	4:50 pm	**Margaret Murnane**, University of Colorado *Center on Real-Time Functional Imaging (STROBE)*
	5:05 pm	Questions & Discussion
5:15 pm		***Panel: The Path from Scientist to Science Communicator***
		Aditi Risbud, Moderator, College of Engineering, UC Davis
		Panelists: **Ben Young Landis** (Capital Science Communicators, California Council on Science and Technology), **Todd Ostomel** (Squire Patton Boggs, Paolo Alto), **Erika Check Hayden** (Science Communication Program, UC Santa Cruz), **Peter Aldhous** (BuzzFeed News, San Francisco), **Nsikan Akpan** (PBS NewsHour, Washington, DC)
6:15 pm		**Walk to Hearst Memorial Mining Building**
6:30 pm		***Wine & Cheese Reception***
7:15 pm		***Dinner***

2018 STC DIRECTORS MEETING: PROGRAM SCHEDULE

WEDNESDAY, AUGUST 22, 2018

7:30 am		**Breakfast**	
8:00 am		***STC Presentations (Class of 2010)***	
	8:05 am	**Erik Goodman**, Michigan State University *Center for the Study of Evolution in Action (BEACON)*	
	8:20 am	Questions & Discussion	
	8:25 am	**Jan Amend**, University of Southern California *Center for Dark Energy Biosphere Investigations (C-DEBI)*	
	8:40 am	Questions & Discussion	
	8:45 am	**Roger Kamm**, Massachusetts Institute of Technology *Center for Emergent Behaviors of Integrated Cellular Systems (EBICS)*	
	9:00 am	Questions & Discussion	
	9:05 am	**Ananth Grama**, Purdue University *Center for Science of Information (CSoI)*	
	9:20 am	Questions & Discussion	
	9:25 am	**Eli Yablonovitch**, UC Berkeley *Center for Energy Efficient Electronics Science (E3S)*	
	9:40 am	Questions & Discussion	
	9:45 am	**Project ENGAGES** video presentation *(EBICS)*	
9:55 am		**Break**	
10:10 am		***Panel: Communicating Effectiveness – The Role of Evaluation***	
		Catherine Amelink, Moderator, Center for E3S, Virginia Tech	
		Panelists: **Lizanne DeStefano** (CBMM, Georgia Institute of Technology), **Lubi Lenaburg** (CNSI, UC Santa Barbara), **Cynthia Phillips** (Office of Integrative Activities, National Science Foundation), **Lea Marlor** (E3S, UC Berkeley)	
11:00 am		***Communicating Across Differences***	
		Patricia Raun, Center for Communicating Science, Virginia Tech	
11:30 am		***Breakout Sessions***	***Workshop (11:30–12:45 pm)***
		STC Directors STC Managing Directors STC Education/Diversity Directors	**Patricia Raun**, Virginia Tech *"Communicating science: Learning to listen, listening to learn"*
12:20 pm		***Reports from Breakout Sessions***	
12:50 pm		***Concluding Remarks***	
		Eli Yablonovitch & **Michael Bartl**, Center for E3S, UC Berkeley	
1:00 pm		**Boxed Lunch**	
1:30 pm		***Optional: Visit of the Exploratorium***	

Appendix I: 2018 Women in Tech Initiative Workshop

A Virtual Reality Event on Gender Bias in Tech

Experience what it's like to be a young female coder in a male-dominated startup.

WOMEN IN TECH INITIATIVE
UNIVERSITY OF CALIFORNIA

WOMEN IN TECH INITIATIVE
UNIVERSITY OF CALIFORNIA

WITI@UC is committed to **addressing the disproportionate participation of women in engineering and computer science fields** by serving as a trusted center and resource that integrates research with action anchored at the University of California.

In 2017, CITRIS & the Banatao Institute and UC Berkeley's College of Engineering came together to launch the Women in Technology Initiative at the University of California, building on the prior efforts on behalf of women technologists of Professor and Vice Provost Tsu-Jae King Liu and Dr. Camille Crittenden, both of UC Berkeley. Interdisciplinary research findings will guide our work in:

- Promoting and sustaining the career growth of women technologists: reducing attrition, supporting career growth in line jobs, increasing technology leadership roles for women in industry and academia
- Increasing access to a range of technology workplace settings: established tech companies as well as startups
- Facilitating and documenting improvements within companies: metrics & measurement, reporting organizational progress
- Coordinating programs: collaboration among the top educational institutions that supply talent to the tech industry in Silicon Valley: the University of California campuses, Stanford University, San Jose State University

Appendix J: 2018 E^{3}S Annual Retreat Agenda

9th Annual Retreat
Center for Energy Efficient Electronics Science

September 20-21, 2018
MLK Building
University of California, Berkeley

AGENDA

Day 1 (Morning) – Thursday, September 20, 2018
MLK Building, Tilden Room (5th floor)

Time	Activity / Topic	Speakers
7:30 AM	***Breakfast & Check-In***	
8:00 AM	**Welcome & Introduction**	
	Review of Agenda	
	Goals for the Retreat	**Eli Yablonovitch**
	Center Overview	
8:30 AM	**Theme I: Nanoelectronics**	
	Theme I Overview	**Eli Yablonovitch**
	Progress on Graphene Nanoribbon Project	**Steven Louie**
	Progress on III-V Nanowire Transistor Project	**Jesús del Alamo**
	Progress on 2D Chalcogenide Transistor Project	**Ali Javey**
	Open Discussion	
9:55 AM	***Break & Poster Set-Up***	
10:05 AM	**Theme II: Nanomechanics**	
	Theme II Overview	**Tsu-Jae King Liu**
	Progress on NEM Relay Project	**Sara Fathipour**
	Progress on Squitch Project	**Jinchi Han**
	Progress on Stritch Project	**David Zubia, Aldo Vidana**
	Open Discussion	
11:20 AM	**System Integration**	
	System Integration Overview	**Vladimir Stojanović**
	Open Discussion	
11:50 AM	***Lunch and Poster Session***	

2018 E3S Annual Retreat Agenda

Center for Energy Efficient Electronics Science

9th Annual Retreat
Center for Energy Efficient Electronics Science

September 20-21, 2018
MLK Building
University of California, Berkeley

AGENDA

Day 1 (Afternoon) – Thursday, September 20, 2018

MLK Building, Tilden Room (5th floor)

Time	Activity / Topic	Speakers
1:10 PM	**Theme III: Nanophotonics**	
	Theme III Overview	**Ming Wu**
	Progress on Antenna-Enhanced LEDs	**Seth Fortuna**
	Progress on New Antenna Coupling Structure	**Sean Hooten**
	Progress on III-V Epitaxy Heterostructures	**Jeehwan Kim**
	Open Discussion	
2:25 PM	***Break***	
2:45 PM	**Theme IV: Nanomagnetics**	
	Theme IV Overview & Progress on Ultrafast Magnetic Switching	**Jeffrey Bokor**
	Spin-Orbit Torque Switching Using Topological Effects	**Shan Wang**
	Topological Insulator Spintronics	**Niklas Roschewsky**
	Progress on Magnetic Tunnel Junction Switching	**Sakhrat Khizroev**
	Open Discussion	
4:00 PM	***Walk to Women's Faculty Club***	
4:30 PM	**Parallel Sessions in Women's Faculty Club:** • Faculty and Industry Partners: Feedback & Discussion Meeting (Boardroom) • Students and Postdocs: Professional Development Workshop (Lounge)	
5:30 PM	***Walk to Berkeley Faculty Club***	
5:45 PM	**Dinner and Recognitions**	
	Heyns Room (Faculty Club)	

2018 E3S Annual Retreat Agenda

9th Annual Retreat
Center for Energy Efficient Electronics Science

September 20-21, 2018
MLK Building
University of California, Berkeley

AGENDA

Day 2 (Morning) – Friday, September 21, 2018

MLK Building, Tilden Room (5th floor)

Time	Activity / Topic	Speaker / Facilitator
7:30 AM	***Breakfast***	
8:00 AM	**Center Management**	
	Management, Metrics, Knowledge Transfer	**Michael Bartl**
	Open Discussion	
8:30 AM	**Education and Diversity**	
	Overview, Challenges, Legacy	**Kedrick Perry**
	Update on E3S e-book	**Farnaz Niroui**
	Diversity Session	**Kedrick Perry**
	Open Discussion	
10:00 AM	***Break***	
10:15 AM	**A Look Beyond 2020: Center Legacy**	
	Breakout Sessions	
	Reporting from Breakout Sessions	**Vladimir Bulović**
	Open Discussion	(Moderator)
11:55 AM	**Closing Remarks**	**Eli Yablonovitch**
12:00 PM	***Lunch (boxed)***	
12:30 – 2:00 PM	**Executive Committee ONLY** **ExComm Meeting**	

2018 E3S Annual Retreat Agenda

Appendix K: 2018 Annual Retreat Poster List

LIST OF POSTERS

Theme 1: Nanoelectronics

Fangzhou Zhao, Ting Cao, Yea-Lee Lee, Steven G. Louie, "Designing Graphene Nanoribbon Transistors for Future Electronics"

Xin Zhao, Christopher Heidelberger, Eugene A. Fitzgerald, Wenjie Lu, Alon Vardi, Jesús A. del Alamo, "Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs: Ni vs. Mo Contacts"

Sri Krishna Vadlamani and Eli Yablonovitch, "Spectral Line Shapes that Control Tunnel Switching Steepness"

Pin-Chun Shen, Jiayuan Zhao, Yuxuan Cosmi Lin, Nannan Mao, Yunan Gao, William A. Tisdale, Jing Kong, "Growth Condition Control Defines 2D Materials Geometry and Other Properties"

Greg Veber, Raymond Blackwell, Dhariti Joshi, Rebecca Durr, Alin Kalinyan, Alexandra Berl, Wade Perkins, Cameron Rogers, Steven Louie, Felix Fischer, "Synthesis and Applications of Graphene Nanoribbons"

T. Patrick Xiao and Eli Yablonovitch, "Artificial Intelligence by Analog Simulated Annealing"

Luis D. Hurtado, Ethan S. Lee, Jesûs A. del Alamo, "Frequency Dependence of AC On-State TDDB for GaN Metal-Insulator-Semiconductor High-Electron-Mobility Transistors"

Theme 2: Nanomechanics

Sergio Almeida, Robert Sifuentes, Tsu-Jae King Liu, "Micro-Electro-Mechanical Relays for Low Power Electronics under Extreme Temperatures"

Sara Fathipour, Sergio Almeida Loya, Benjamin Osoba, Alice Ye, Farnaz Niroui, Tsu-Jae King Liu, Junqiao Wu, "Surface Molecular Coating for Adhesion Minimization in NEM Switches"

Jinchi Han, Farnaz Niroui, Timothy Swager, Jeffrey Lang, Vladimir Bulović, "Tunneling NEM Switch Based On Compressible Molecules (Squitch)"

Raquel Zubia, Mariana Martinez, Jose Mireles, Edgar Acosta, Aldo Vidana, Sergio Almeida, David Zubia, "Design and Simulation of Scalable Electro-Mechanical Device for Information Processing"

Zhixin Alice Ye, Sergio Almeida, Miles Rusch, Angelica Perlas, Wenyi Zhang, Urmita Sikder, Jaeseok Jeon, Vladimir Stojanović, Tsu-Jae King Liu, "Demonstration of 50-mV Digital Integrated Circuits with Microelectromechanical Relays"

Edgar Acosta, Marianna Martinez, Aldo Vidana, Sergio Almeida, Jose Mireles, David Zubia, "SOI MEMS for Strain-Engineered 2D Materials"

Theme 3: Nanophotonics

Kevin Han, Seth Fortuna, Sujay Desai, Matin Amani, Ali Javey, Eli Yablonovitch, Ming C. Wu, "TMDC Based nanoLEDs for High-Speed Energy-Efficient Optical Interconnects"

Nicolas M. Andrade, Sean Hooten, Krishna T. Settaluri, Seth Fortuna, Kevin Han, Eli Yablonovitch, Vladimir Stojanovic, Ming C. Wu, "Inverse Design for Single-Mode Coupling of Electrically Injected Optical Antenna Based nanoLED"

Seth A. Fortuna, Christopher Heidelberger, Nicolas Andrade, Kevin Han, Sean Hooten, Eli Yablonovitch, Eugene A. Fitzgerald, Ming C. Wu, "Fast Spontaneous Emission in a III-V Antenna-LED"

Sean Hooten, Ming Wu, Eli Yablonovitch, "Metal-Dielectric Structure for Spontaneous Emission Enhancement of Point Radiation Sources"

Theme 4: Nanoelectronics

Dennis Toledo, Mark Stone, Brayan Navarrete, Ping Wang, Kevin Luongo, Vladimir Safonov, Jeongmin Hong, Jeffrey Bokor, Sakhrat Khizroev, "Quantum Size Effect in Sub-10-nm Co Cube: Illustration of the Surface and the Volume Effects"

Xiang (Shaun) Li, Chong Bi, Shan X. Wang, "Harnessing Embedded Magnetic Memory and Logic for Artificial Intelligence Applications"

Akshay Pattabi, Jon Gorchon, Yang Yang, Charles-Henri Lambert, Richard Wilson, Sayeef Salahuddin, Jeffrey Bokor, "Ultrafast single-shot magnetization reversal in ferromagnetic Co/Pt multilayers"

2018 E3S Annual Retreat Agenda

Center for Energy Efficient Electronics Science

Appendix L: 2018 Student and Postdoc Survey

Year-to-Year Comparison

Part A: Teamwork, Inclusiveness, Leadership, Decision Making and Performance

Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree

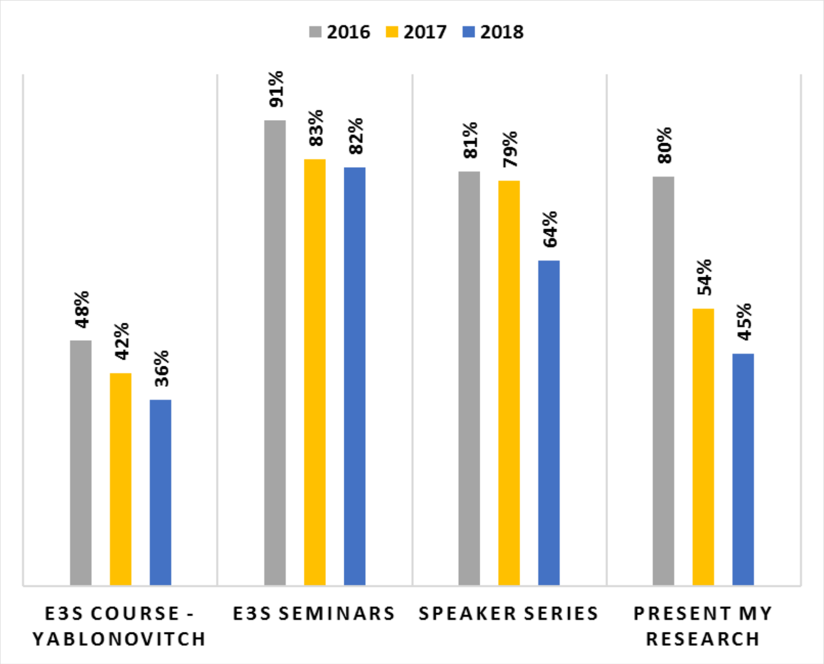
		2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
	Total Number of Respondents	20	21	26	29	22	24	22
	Survey Questions							
Research	The Leadership Team identifies concepts and scientific principles that will enable fundamentally new and different science for digital information processing, in order to achieve a radical reduction in energy consumption in electronic devices.	4.2 ± 0.7	4.4 ± 0.5	4.6 ± 0.6	4.4 ± 0.6	4.3 ± 0.9	4.4 ± 0.6	4.5 ± 1.0
	The Center is making progress in its research program.	4.2 ± 0.5	4.1 ± 0.9	4.5 ± 0.6	4.4 ± 0.7	4.4 ± 0.9	4.4 ± 0.7	4.6 ± 0.9
	I understand how my project will contribute to the goals and vision of the Center.	4.3 ± 0.9	4.5 ± 0.6	4.5 ± 0.7	4.6 ± 0.5	4.8 ± 0.8	4.3 ± 0.8	4.3 ± 1.1
Inclusiveness	The Leadership Team educates a diverse generation of scientists, engineers and technicians to be the future leaders, researchers, educators and workers of low energy consumption device science and technology.	4.1 ± 0.6	4.1 ± 0.8	4.6 ± 0.5	4.3 ± 0.9	4.3 ± 1.0	4.4 ± 0.8	4.5 ± 1.0
	The Leadership Team provides a research environment that is inclusive of different institutions, research themes, science and engineering disciplines, and individual differences.	4.1 ± 0.6	4.0 ± 0.9	4.7 ± 0.5	4.6 ± 0.6	4.5 ± 0.7	4.5 ± 0.6	4.5 ± 0.9

	The Leadership Team provides a research environment that crosses disciplinary and institutional boundaries.			4.5 ± 0.7	4.4 ± 0.8	4.2 ± 0.9	4.5 ± 0.6	4.6 ± 0.9
Communication	The Leadership Team keeps Center members well informed as there is a clear and timely communication on all Center activities.	4.2 ± 0.5	4.2 ± 0.6	4.7 ± 0.6	4.2 ± 0.8	4.4 ± 0.8	4.5 ± 0.5	4.4 ± 1.1
Collaboration	The Leadership Team provides a research environment that is collaborative.	4.2 ± 0.7	4.2 ± 0.7		4.3 ± 0.8	4.3 ± 0.8	4.5 ± 0.6	4.5 ± 1.0
	The Leadership Team is providing a work environment that values and encourages teamwork.		3.9 ± 0.8	4.6 ± 0.5	4.4 ± 0.8	4.4 ± 0.8	4.4 ± 0.6	4.5 ± 0.9
	The Leadership Team is providing opportunities to collaborate.		4.1 ± 0.9	4.8 ± 0.4	4.2 ± 1.0	4.3 ± 0.9	4.4 ± 0.6	4.4 ± 1.1
	The Leadership Team is providing tools that facilitate collaboration.		4.1 ± 0.7	4.4 ± 0.8	4.3 ± 1.1	4.3 ± 0.9	4.4 ± 0.8	4.3 ± 1.1
	Since joining the Center, I have developed a working relationship with someone in the Center who is not part of my home institution.	3 ± 1	4 ± 1	4 ± 1	4 ± 1	3.5 ± 1.5	3.7 ± 1.3	3.6 ± 1.4
Decision Making	The Leadership Team is effective in making decisions on behalf of the Center.	4.1 ± 0.6	4.2 ± 0.7		4.5 ± 0.6	4.5 ± 0.8	4.4 ± 0.7	4.4 ± 0.9
	The Leadership Team is agile in making decisions on behalf of the Center.	4.1 ± 0.7	4.1 ± 0.9		4.5 ± 0.6	4.4 ± 0.8	4.4 ± 0.7	4.3 ± 1.0
	The Leadership Team is making decisions that are in the best interest of the Center.			4.5 ± 0.6	4.4 ± 0.6	4.3 ± 0.7	4.3 ± 0.5	4.4 ± 0.9

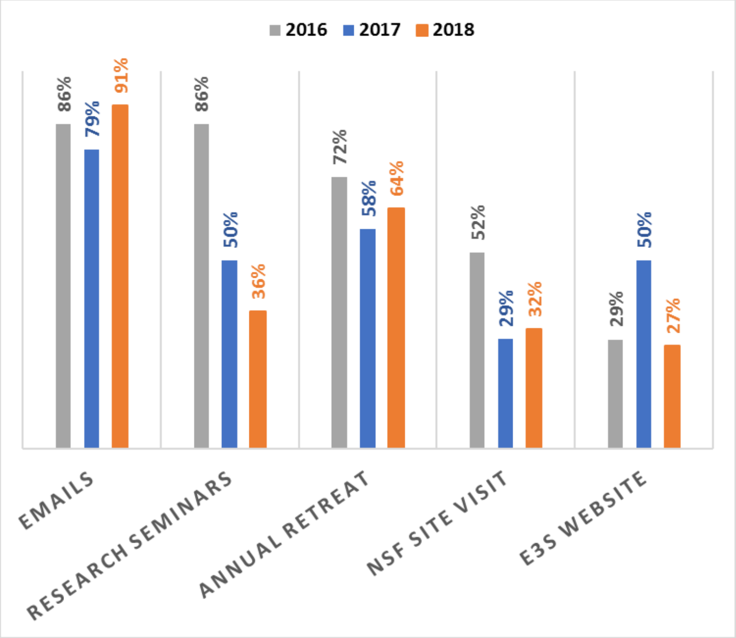
Performance Focus	The Leadership Team promotes a culture permeating the Center's relationships, processes, and activities that recognize and values performance, and avoids possessiveness.	3.9 ± 0.9	4.1 ± 0.7	4.5 ± 0.6	4.3 ± 1.0	4.3 ± 0.9	4.3 ± 0.6	4.3 ± 1.0
	The Leadership Team is recognizing and evaluating me on my performance.		3.8 ± 1.0	4.4 ± 0.7	4.0 ± 1.0	4.1 ± 1.0	4.0 ± 0.9	3.6 ± 1.3

Part B: Effectiveness of the Center's Activities

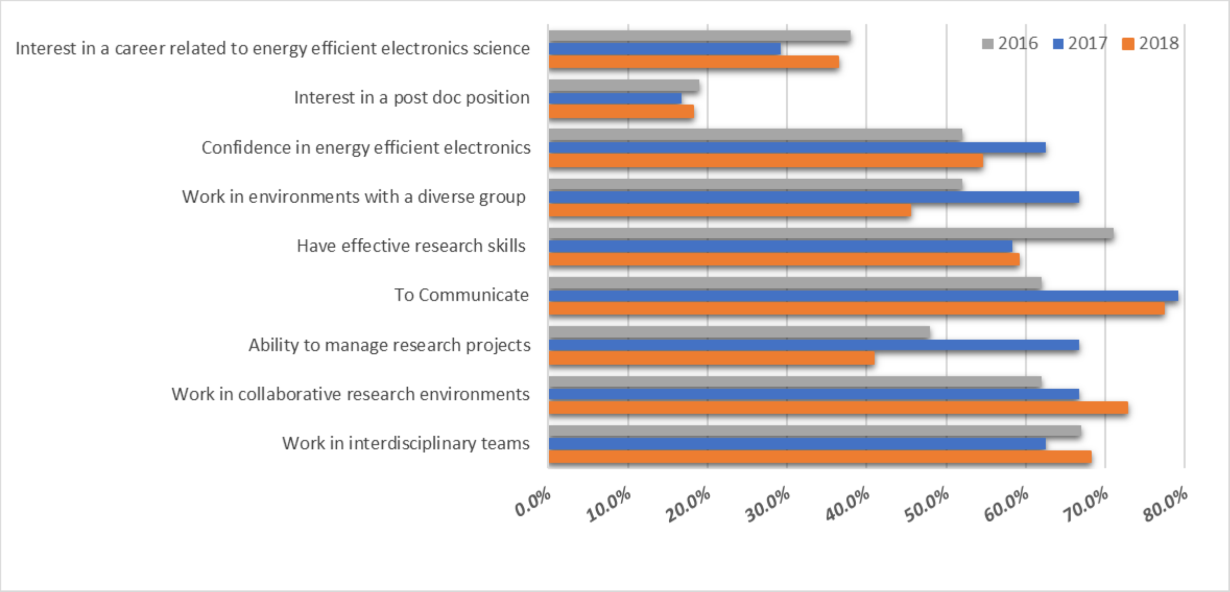
1. Respondents indicated the following activities are sharpening their understanding of low energy consumption device science and technology.



2. Respondents felt that the Center communicates with them effectively and in a timely manner using the following resources.

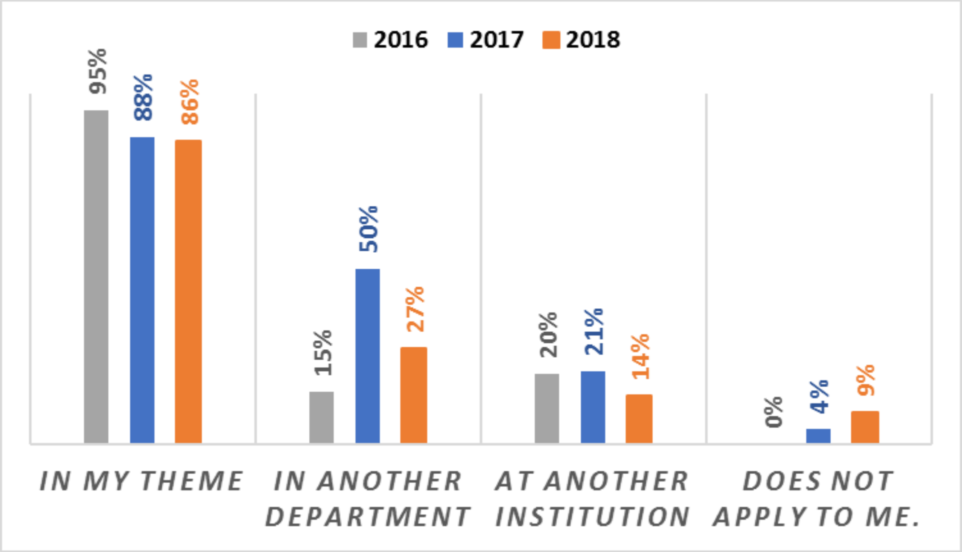


3. Respondents identified the following areas were positively impacted as a result of their experience at E^{3}S.

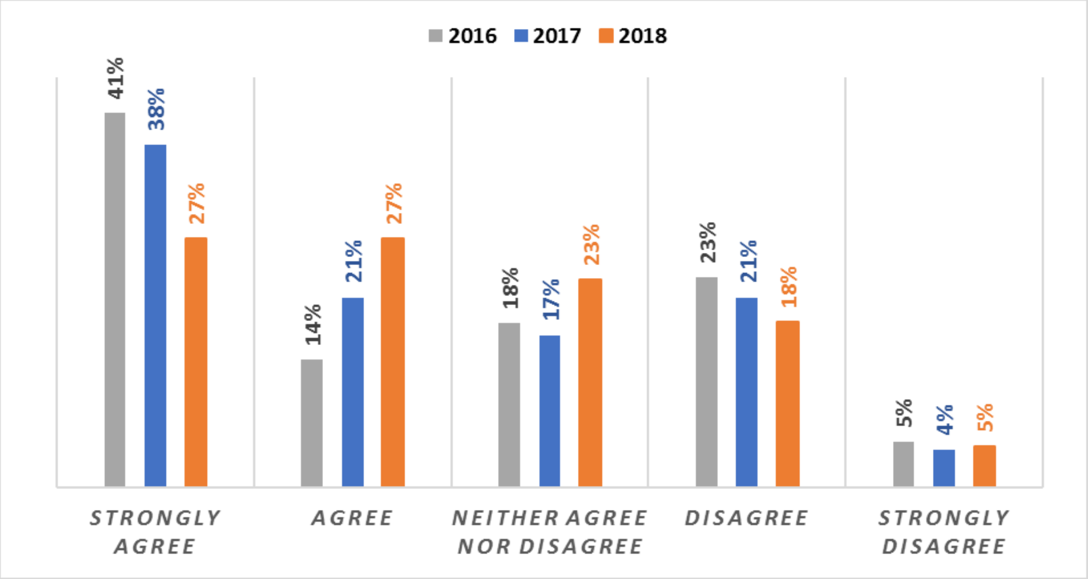


Part C: State of Collaborations

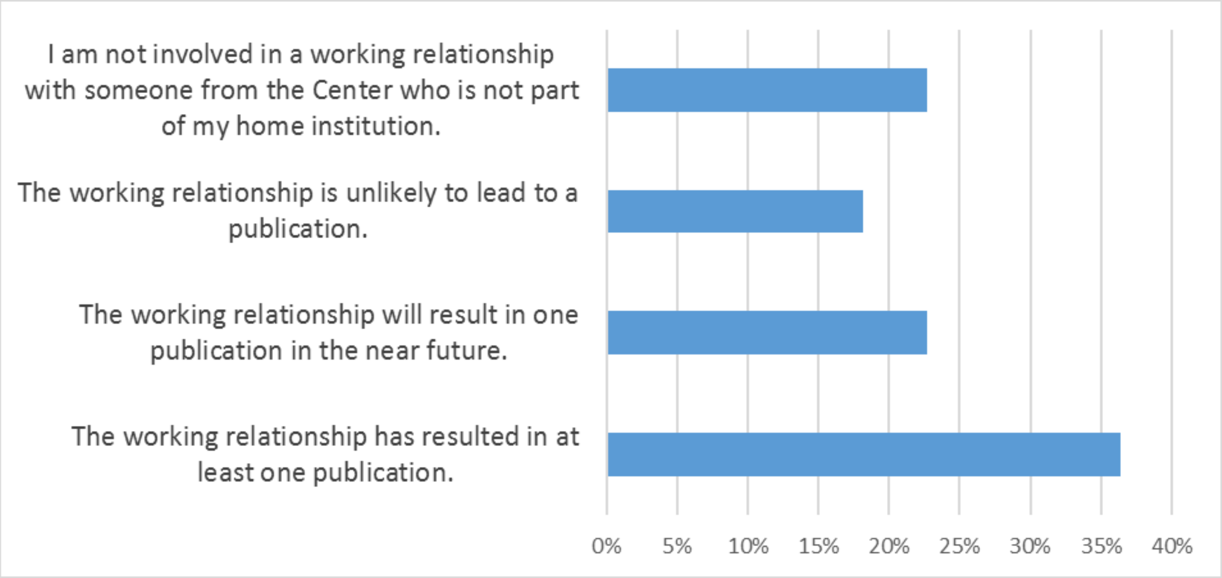
1. Respondents indicated that the following people helped with their E^3S research.



2. Respondents have developed a working relationship with someone in the Center who is not part of their home institution.



3. Respondents’ collaboration with someone in another institution has or will have the following results.



Part D: Ethics

100% of respondents felt that their E^{3}S colleagues acted in an ethical manner.

Appendix M: 2018 E^{3}S Faculty Survey

Year-to-Year Comparison for Last Three Years

Leadership Survey

Responses in Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree

The E^{3}S leadership team is dedicated to:	**2015**	**2016**	**2017**	**2018**
Creating an inclusive work environment.	4.9±0.2	4.9±0.2	4.8±0.4	4.9±0.3
Promoting a work environment that values and encourages teamwork.	4.9±0.3	4.9±0.2	4.8±0.4	4.9±0.2
Providing open and timely communication to me.	4.7±0.6	4.8±0.4	4.8±0.4	4.8±0.4
Recognizing and evaluating me on my performance.	4.7±0.6	4.3±0.8	4.7±0.6	4.7±0.4
Making decisions that are in the best interest of the Center.	4.8±0.4	4.8±0.4	4.8±0.4	4.8±0.4
Providing opportunities to collaborate.	4.9±0.3	4.8±0.4	4.8±0.4	4.9±0.3
Providing tools that facilitate collaboration.	4.6±0.6	4.7±0.5	4.7±0.6	4.8±0.4
Educating a diverse generation	4.9±0.3	4.9±0.3	4.8±0.4	4.9±0.3
Identifying fundamentally new concepts and scientific principles	4.9±0.2	4.8±0.4	4.8±0.4	4.9±0.2

2018 sampling size: 19

In addition, all respondents answered the question "*I feel that my E^{3}S colleagues act in an ethical manner*" with YES.