Center for Energy Efficient Electronics Science

Final

Period 8 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	January 30, 2018
Reporting period	March 1, 2017– February 28, 2018
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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.

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

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Role of Institution at Center	UTEP is a research, education, and outreach partner to encourage greater minority participation in engineering.

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Role of Institution at Center	FIU is a research, education, and outreach partner to encourage greater minority participation in engineering.

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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*

N/A

1c. *Primary Contact Person*

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

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2. *Context Statement*

The Center for Energy Efficient Electronics Science (E^3S) is a Science and Technology Center funded by the U.S. National Science Foundation. Since its inception in 2010, the Center for E^3S has employed a multi-faceted approach, including research, education, diversity, outreach and knowledge transfer activities, with the goal to revolutionize electronics and information processing by developing highly energy-efficient logic switches. The Center pursues this goal through education of a diverse generation of scientists and engineers to be the future leaders, researchers, educators, and technicians for new low-energy device science and technology. The Center for E^3S strives to promote the application of its research and education outcomes to become the foundation for low-energy electronic systems.

Recent advancements in cloud computing, social networking, mobile internet and data analytics have driven a rapid growth in the demand for information processing speed and bandwidth. This growth is accompanied by increasing importance of wireless sensor swarms, body-centered networks, data centers and servers, and supercomputers. Information processing consumes a significant fraction (4 percent) of the total electricity production in the U. S., with increasing growth. Moreover, there is an increasing use of battery powered electronic systems. However, at the most fundamental level, the energy used to manipulate a single bit of information is currently about 100,000 times greater than the theoretical limits. In order to address this issue, there is a critical need for fundamental and conceptual breakthroughs in the underlying physics, chemistry, materials science and device engineering that form the foundation of information-processing technologies.

The defining research goal of the Center for E^3S is to provide the science and fundamental knowledge needed for developing electronic systems approaching the theoretical limits of energy efficiency in logic switching. This ambitious goal is being pursued through a collaborative approach, involving engineers, chemists, physicists, and materials scientists from the 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*). These five core institutions work in close collaboration with various community colleges, as represented by the California Community College System's Chancellor's Office, and with industrial partners Applied Materials, IBM, Intel Corporation, HP Enterprise, and Lam Research.

Conventional transistors, for all their success in forging today's interconnected society, suffer from a serious drawback: their conduction is thermally activated. As a consequence, powering voltages of ~0.8 Volts are required to provide a good ON/OFF current ratio, even as transistors become smaller and smaller. The wires connecting the transistor, however, 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. Therefore, a more sensitive, lower-voltage switch is needed as the successor to the conventional transistor. The need for lower voltage is paramount as most of the energy goes for charging interconnect wires.

Now in its eight year, the Center for 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 and different digital-information processing science. The Center for E^3S researchers recognized early on that a new ultra-low energy switch must meet a set of key specifications to be of practical use. The three most important specifications are:

- Steepness (or sensitivity): ~1 mV/decade; to enable switching with a 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.)

Additionally, the Center pursues an optical communication strategy to replace some longer metal interconnects with Si optical waveguides. That 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.

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 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 8, 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 at 10 mV, that would be 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. Theoretical predictions promise excellent steepness, On/Off ratios and conductance for tunnel transistors [1]. So far, experimental research results around the world are rather disappointing. While leading results show that tunnel distance modulation is steep at low currents [2-5], 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.

As has been emphasized by E^{3}S researchers [6, 7], 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. The latter is also called the energy filtering mechanism and projects high conductance in the ON-state. Since the goals of the Center for E^{3}S are far beyond a 2-fold reduction of the operating voltage, achievable by current tunnel-distance-modulation devices, nanoelectronics researchers at E^{3}S have focused on elucidating the underlying device physics, which could lead to orders of magnitude energy reduction, as opposed to moderate device optimization as being pursued by industry. Theme leader **Eli Yablonovitch**, guided the research in nanoelectronics toward the preferred density-of-states mechanism. This demands higher materials interface perfection than ever previously required or achieved in solid-state electronics. Owing to these findings, a significant portion of the research effort in the E^3S nanoelectronics theme has focused on identifying, synthesizing and incorporating the new two-dimensional materials that promise excellent surface and interface properties and low defect densities.

In period 8, 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.

The second and dominating research effort of the nanoelectronics theme has been the search for new material systems with ultra-low interfacial defect states. 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, further decrease the defect density of these new semiconductors by superacid treatment and scanning probe methods, and to integrate low defect-density 2D chalcogenides into tunnel device structures. The Center's bottom-up synthesis of graphene nanoribbon semiconductors has been led by synthetic organic chemist, **Felix Fischer** (*Berkeley*). These structures exploit lateral quantum confinement to produce a tunable bandgap. Current goals of this project focus on 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 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 are investigated to apply zero-leakage NEM-based switching in a system application. Mechanical switches can achieve very low OFF-state leakage (I_{OFF}) and abrupt switching behavior across a wide range of temperatures [8]. In principle, they can be operated with much lower voltage than current transistors. Realizing that surface adhesion ultimately limits relay scaling, the Center has focused on new approaches that go beyond voltage reduction through scaling and new device design. In addition, 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 or 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 8, the goals of the nanomechanics research efforts have focused on further lowering the contact adhesion energy of electromechanical switches, fabricating a four-terminal operating squitch device, conducting an energy analysis of the stritch concept, and demonstrating a NEM relay-based integrated circuit operation. The groups of **Tsu-Jae King Liu** and **Junqiao Wu** (both *Berkeley*) have continued to investigate minimization of hysteresis voltage of NEM switches by using anti-stiction molecular electrode coatings in the form of self-assembled monolayers. Different molecules have been investigated as coatings with the goal of achieving sub-10 mV hysteresis voltages. **Vladimir Stojanovic** (*Berkeley*) has been leading the system integration efforts. System integration has continued to provide a path to quantifying the benefits of the emerging device technologies at the circuit/system level and give guidance to the device designers by identifying which device design parameters are of critical importance to improve properties at the system level. In collaboration with the **Liu** group, period 8 goals include demonstration of a functional NME-based multiplexer circuit at sub-100 mV operation.

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 demonstrate fabrication of a four-terminal squitch device that can be scaled to circuit-level complexity. 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. 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 a full energy analysis of the stritch device, including a comparison to the CMOS inverter.

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 experimentally approach 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, E^{3}S researchers recognized early on that ultra-efficient and sensitive optical components need to be developed so that they can be integrated with waveguides as well as miniaturized to be comparable to the size of transistors.

On the emitter side, the groups of **Ming Wu**, **Eli Yablonovitch** and (all *Berkeley*) and **Eugene Fitzgerald** (*MIT*) continue to optimize design and properties of antenna enhanced nanoLEDs. 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, which are currently the ubiquitous light source in optical communications [10]. The goals in this period are to demonstrate spontaneous emission enhancements of >200 times under direct electrical-excitation of III-V antenna nanoLEDs and to improve efficiency of chalcogenide nanoLEDs under electrical excitation.

At the systems level, photoreceiver research has been of equal importance to the novel antenna-LED emitter approach. However, circuits and systems analysis performed in the last period by **Vladimir Stojanovic** (*Berkeley*) in collaboration with the **Yablonovitch** and **Wu** groups revealed that the photodetector needs be of sufficient size to absorb the photons, while the nano-scopic, short-transit-time, high-speed pre-amplifier must be ultra-small, presenting mutually conflicting requirements [11]. Thus the photo-transistor effort in the Center, which tried to combine both functions in a single device, had been eliminated at the end of period 7. Instead, **Constance Chang-Hasnain** will invert the antenna-LED concept to determine whether an antenna-photodetector can provide photonic systems advantages. In period 8, Center director **Eli Yablonovitch** will continue to present our detector/pre-amp circuit insights to representatives of the silicon photonics industry, who appeared to be poised to adopt these innovations, which would greatly improve data throughput and reduce the all-important energy/bit number. If this serendipitous technology spinout occurs, that will be one of the important successes of the Center for E^{3}S.

Theme IV: Nanomagnetics

The nanomagnetic 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 nanophotonics theme, 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 [12]. 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.

In the last period, the groups of **Jeffrey Bokor** and **Sayeef Salahuddin** (*Berkeley*) demonstrated ultrafast switching in the picosecond time range enabled by hot electron magnetic quenching and re-orientation via direct electron heating from a short electrical pulse [13]. We have already achieved magnetic switching speed in the range of a few to 10 picoseconds, but we need to maintain total switching energy to be similar or lower than current state of the art. Furthermore, in a joint collaboration led by **Philip Wong** (*Stanford*), the **Bokor** and **Salahuddin** groups focus on integrating these high-speed magnetic switches into advanced CMOS chips in order to test ultra-fast magnetic switching triggered by electrical pulses generated directly within the CMOS circuits. The portion of the spin-orbit torque research by the **Salahuddin** group is 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 combining spin-Hall metals with two different spin-Hall angles as a new way of reducing switching current. 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.

On the circuit/system level, the **Stojanovic** and **Wong** groups have focused on further 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. Several spin-based devices added to SRAM circuits were investigated in terms of enabling non-volatile operation and saving energy during the power-gating cycles of the processor. The experimental efforts by the **Wong**, **Bokor** and **Salahuddin** groups have focused on integrating three-terminal spin Hall memory devices with FETs to build SRAM and flip-flops, and to show that the circuits are nonvolatile and have no impact on circuit area. The result would be high-speed non-volatile SRAM flip-flops.

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 required to complete online ethics training. 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. This year the Center offered a comprehensive science communication workshop for the students and postdocs that attended the Center's annual retreat.

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 six 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^3S or E^3S affiliated faculty, have been transferring to four-year institutions since Fall 2012 at a rate of 93%, 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^3S 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^3S member institution, they do not pursue a thesis in an E^3S area of research. The Center recognized this difficulty and addressed the challenge through structural changes. In period 6, the E^3S 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^3S faculty. In addition, they also have the option to develop new teaching materials advised by E^3S 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 an outline of this book while Theme 2 has taken the lead and completed much of a first draft.

Knowledge Transfer

As an NSF Science and Technology Center, the mission of E^3S is to foster groundbreaking scientific discoveries and fertilize new technologies. Knowledge transfer is thus at the heart of the Center for E^3S and knowledge transfer activities and outcomes are considered a key metric of its success. Since the inception of the Center, E^3S 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^3S 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 recognized that the preparation of the next generation of scientists, engineers and technicians is also a community endeavor. 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 8

In this section, a summary of the progress of the Center for E^{3}S in period 8 is presented. Details and in-depth analyses of the results are given in the following sections of this report.

The state of the Center is presented with respect to the E^{3}S Strategic Plan 2015-2020, and the metrics established therein. The Center has recognized that 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 E3S Performance Targets and Results*

Objective	Metric	Targets	Results						
			P 2	P 3	P 4	P 5	P 6	P 7	P 8
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)
	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)
	Publications with authors from multiple institutions	P3: 12 P4: 3 P5: 5 P6: 5	0	1	1	1	3	4	4

		P7: 5 P8-P10: 5							
	New joint research funding awards	P6: 1 P7: 0 P8-P10: 1	(new for P6-10)				0	3	1
Education	Center graduates completed E^{3}S training	P2: Baseline P3: 50% P4: 50% P5: 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%)
	Students accessing online courses of the Center	P6: 50 P7: 75 P8: 110 P9: 170 P10: 250	(new for P6-10)				0	0	0
	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%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P2: Baseline P3: 5% P4: 80% P5: 80% P6: 85% P7: 85% P8-P10: 85%	n/a	3 (100%)	6 (100%)	7 (100%)	6 (100%)	4 (80%)	4 (60%)

	Pre-college students who pursue a bachelor's degree in science and engineering	P3: Baseline P4: 70% P5: 70% P6: 80% P7: 80% P8-P10: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)	180 (47%)
	Students and postdocs serving in leadership roles in the Center	Period 2: Baseline P3: 15% P4: 20% P5: 25% P6: 30% P7: 30% P8: 30% P9: 20% P10:15%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)	14 (16%)
Diversity	Women in the Center's research programs	P2: Baseline P3: 5% increase P4: 30% P5: 20% P6: 25% P7: 25% P8-P10: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)	12 (14%)
	Underrepresented minorities in the Center's research programs	P2: baseline P3: 15% increase P4: 5% P5: 10% P6: 10% P7: 12% P8: 12% P9-10: 15%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)	11 (13%)
	Participants from underrepresented* groups in the Center's Diversity programs	P3: Baseline P4: 80%	n/a	93 (82%)	Women 37 (44%)	Women 26 (41%)	Women 29 (40%)	Women 25 (40%)	Women 38 (44%)

		P5: 85% P6: 85% P7: 85% P8-P10: 85%			URM: 58 (68%) Total: 73 (86%)	URMs 36 (56%) Total 49 (77%)	URMs 49 (67%) Total 66 (90%)	URMs 38 (60%) Total 63 (87%)	URMS 48 (55%) Total 69 (80%)
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center	P 6: 40% P7: 45% P8-P10: 50%	(new for P6-10)				17 (55%)	23 (54%)	27 (50%)
	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%)
	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%)
Knowledge Transfer	Center publications	P2: 18 P3: 18 P4: 18 P5: 18 P6: 25 P7: 25 P8-P10: 30	17	17	19	39	45	41	39 (7 subm.)
	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26
	Center sponsored symposia & workshops	P2: Baseline P3: 0	1	0	1	0	1	1	2

		P4: 1 P5: 0 P6: 2 P7: 1 P8-P9: 1 P10: 2							
	External citations of publications *(cum)*	P3: 10 P4: 100 P5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase
	Contacts with industry:								
	• Talks & Meetings	All Periods: 36	66	20	42	62	35	42	31
	• Industry Presentations	All Periods: Yearly: 2	4	2	6	3	5	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8
	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
	• Patent/Patent Application	P4: 0 P5: 3 P6: 1 P7-P9: 2 P10: 3	1	2	1	3	8	4	1
	Technologies attributable to Center's research		(new for P6-10)				0	0	0
	• Low energy devices	P6-P9: 0 P10: 1							
	• Enabling other applications	P6: 0 P7: 0 P8-P9: 1 P10: 2							

	Center's alumni into relevant industries	P5: 50% P6: 30% P7: 30% P8-P9: 40% P10: 50%	Students 0% Postdocs 100% (1)	Students 64% (7) Postdocs 33% (2)	Students 16% (2) Postdocs 20% (2)	Students 16% (6) Postdocs 40% (4)	Students 50% (12) Postdocs 13% (1)	Students 22% (2) Postdocs 18% (2)	Students 33% (4) Postdocs 60% (3)
	Center's alumni pursuing research in academia & research labs in disciplines related to the Center	P6-10: 30%	(new for P6-10)				Students 38% (9) Postdocs 88% (7)	Students 78% (7) Postdocs 82% (9)	Students 58% (7) Postdocs 40% (2)
Center Management	Annual Surveys:	According to Likert Scale:							
	• Students /Postdocs	P2: 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
	• Co-PIs	P3: 3 or higher P4: 3 or higher P5: 3 or higher P6-10: 4 or higher	No survey in Period 2	Leader-ship: 4.46 Collabor ation 3.25	Leader-ship: 4.7±0.5 Collabor ation n/a	Leader-ship: 4.9±0.1 Collabor ation Outside Theme: 1.3+/-0.1 Within Theme: 3+/-1	Leader-ship 4.6±0.1	Leader-ship 4.8±0.2	Leader-ship 4.8±0.1
	• External Advisory Board		Strategic Plan: 4.18 Center Status: 4.01	Strategic Plan: 4.07 Center Status: 3.96	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
	Authorship disputes	P2: 20% decrease P3: 20% decrease P4: 20% decrease P5: 20% decrease	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale	0	0	0	0

		P6-10: 0							
	Plagiarism	All Periods: 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

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 8

The Center 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 8, 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*: Dimitri Antoniadis*, Vladimir Bulović, Jesus del Alamo, Eugene Fitzgerald, Jing Kong, Jeffrey Lang, Timothy Swager
- *Stanford*: H.-S. Philip Wong
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

* **Dimitri Antoniadis** (*MIT*) phased out of the Center on 6/30/2017. This decision was made between Prof. Antoniadis and the Center leadership due to the Centers' emphasis on new types of semiconductors.

Theme I: Nanoelectronics – Key Accomplishments

- *III-V Nanowire TFETs:* Vertical nanowire III-V TFET structures fabricated by the **del Alamo** group have proven to be excellent model systems to study the underlying physics of tunneling in semiconductors, while revealing the issue of defect assisted tunneling in the OFF-state [6]. In this period, a new rapid thermal annealing (RTA) step has been developed. This annealing step dramatically improved subthreshold characteristics of top-down InGaAs/InAs heterojunction vertical nanowire TFETs. Sub-thermal subthreshold behavior over two orders of magnitude of current at room temperature were demonstrated; however, at low current density, indicative of the tunnel distance modulation mechanism. Significant progress was made in fabricating vertical nanowire MOSFETs with record small diameters of 15 nm were fabricated. These are the first devices at this dimensional range on any semiconductor system. The devices yielded outstanding subthreshold behavior with a linear subthreshold swing of 69 mV/dec, approaching the ideal value of 60 mV/dec at room temperature. In subsequent work, the **del Alamo** group has shown that changing the top contact metallization from Mo to Ni allows to further shrink nanowire diameter and obtain working InGaAs MOSFETs with a diameter of 7 nm. These are the first vertical nanowire FETs of any kind fabricated on any semiconductor system with a diameter less than 10 nm. As has been shown by the

Yablonovitch group's modeling work, single 1D subband devices will give new insights toward the goal of elucidating the fundamental spectroscopic characteristics of tunneling energy levels. This puts E^3S nanoelectronics researchers in a great position to assess the ultimate current/voltage potential of tunnel switching 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 in this period 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:* With last year's the breakthrough discovery in the **Javey** group that superacid treatment enables "healing" of defects in 2D-TMDCs, their quality was significantly improved (> 95 percent internal quantum yield). In this period, the **Javey** group developed a technique to passivate edge defect sites of 2D-TMDCs, grown by CVD method in the **Kong** group, by using the same superacid method in combination with scanning probe lithography technique for edge patterning. The **Kong** group has also make significant progress in materials characterization, using scanning transmission electron microscopy to examine point defects, and phase modulated optical parametric amplification imaging (PMOPA) to study grain boundaries of 2D chalcogenide materials with a resolution that is close to near field techniques. These various characterization tools are used to compare the defect types and densities in CVD and MOCVD grown materials. Keeping the original goal of high performance TFETs in mind, moving forward, focus will be redirected back on device performance and conducting in-depth studies of the superacid's role on the electrical properties of 2D materials. Additionally, future efforts of integrating superacid treatment into TFET fabrication will also be an important problem to solve.

- *Graphene Nanoribbon Quantum Tunneling Structures:* The **Fischer** group has continued to develop bottom-up synthesis strategies for heterostructure graphene nanoribbons (GNRs). With broad theory support by the **Louie** and **Yablonovitch** groups, particular emphasis in this period was directed towards developing new atomically precise doping strategies by introducing orbitally matched trigonal planar heteroatom dopants to ensure overlap of the heteroatom lone-pairs with the extended π-system. N-, O-, and S-dopant atoms were selected for their varying degrees of electronegativity. Scanning tunneling spectroscopy (STS) studies of these samples revealed a narrowing of the band gap by ~0.2-0.3 eV per dopant atom per monomer unit when compared to unsubstituted GNRs. The correlation of the electronic band structures of doped GNRs establishes rational and predictable structure-function relationships that were corroborated by density functional theory (DFT) calculations by the **Louie** group, using model Hamiltonian methods as well as first-principles calculations.

  The **Louie** group has also identified a new family of molecular precursors for GNRs featuring nitrogen dopant atoms along the backbone of an armchair GNR. This characteristic backbone doping pattern yields GNRs featuring a metallic band structure, which will serve as conductive leads for the semiconducting GNR devices. In response, the **Fischer** group successfully developed a synthesis for these new molecular precursors and, in collaboration with the **Bokor** and **Salahuddin** groups, initiated the first deposition and GNR growth experiments on substrates. The **Louie** group has made another interesting discovery by finding topological phases in GNRs. Using these topological effects, the group designed GNR-based electronic devices with localized junction states by connecting two GNRs of distinct topology. In a superlattice consisting of segments of topological trivial and nontrivial GNRs, the junction states are stable spin centers and may provide a scheme to realize Majorana physics and a platform for quantum computing [14].

Theme II: Nanomechanics – Key Accomplishments

- *Ultra-Low-Voltage Relays:* The **Liu** and **Wu** groups, in collaboration with the **Bulovic**, **Lang** and **Swager** groups, make significant progress in further lowering the contact adhesion energy of nanomechanical relay switches by using improved anti-stiction molecular coatings. A systematic study of the effect, mechanism, and performance of various coating molecules of different chain lengths and functional groups revealed that coatings with molecules with fluorinated functional groups and a chain length of ~1.5 nm are optimal for reducing hysteresis voltage while retaining steep switching behavior. The best result was obtained using the molecule perfluorooctyltriethoxysilane (PFOTES), which reduced the hysteresis voltage from ~100 mV for a non-coated relay to ~20 mV while keeping the subthreshold swing to less than ~10 mV/decade, so that the relay was fully switched between ON and OFF states with sub-50 mV swing. In addition, for relays coated with PFOTES the reduced hysteresis voltage is also more stable over many switching cycles, indicative of more uniform contact properties. Regarding demonstrating ultra-low-voltage operation of relay-based integrated circuits, the **Liu** group has identified variability in relay switching voltage (V_{PI}) as a practical challenge. A non-zero strain gradient within the structural layer was found to mitigate the effect of systematic variation in structural layer thickness but also to cause significant random variation in V_{PI} from device to device. Anti-stiction coating was found to be effective for stably reducing the magnitude and variation in V_H, facilitating reductions V_{DD}. In collaboration with the **Stojanovic** group, successfully demonstration of a 2:1 multiplexer circuit functioning with a supply voltage of only 100 mV was achieved. The **Stojanović** group has also started a new system integration direction by setting up a deep-learning training environment based on the Tensor Flow. This should enable evaluation of various hardware-related architectural tactics (network pruning, reduced resolution, *etc*.) and system-level evaluation of the NEM relay computing architectures.

- *Squitch: Molecular Squeeze-Switch:* The **Bulovic**, **Lang** and **Swager** groups, the **Squitch** team, has developed and successfully executed a new fabrication process for a four-terminal squitch device. The squitch 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. In the new four-terminal device, the active electrode area measured approximately 120 nm by 1200 nm with Au electrodes exhibiting sub-nanometer smoothness and planarity. The movable conductor was a Au smooth nanorod, approximately 100 nm in diameter, and 1500 nm in length. A single nanorod was moved into position using dielectrophoresis and was supported above the electrodes by a compressible PEG-thiol self-assembled monolayer with an approximate unactuated spacing of 4 nm. The measured squitch performance indicated that the gap did compress with increasing gate voltage. The modeled compression indicated a 20-MPa mechanical modulus for the PEG monolayer, which is consistent with the bulk modulus reported for PEG in literature. At a gate-gate voltage of approximately 2.4 V, the squitch exhibited pull-in and a 1000-fold increase in drain current. These results are the first demonstration of a gated metal-molecule-metal (squitch-like) tunneling gap and current.

  Furthermore, experiments showed the behavior to be very repeatable and absent of stiction that is common in ordinary relays. The squitch also exhibited narrow hysteresis as it traverses a closing-opening cycle. With these promising results, the **Squitch** group has started with an important next step in this project by extending the new fabrication process flow to enable the fabrication of many interconnected squitches. The squitches can be connected by wire bonding to pads. This is a first step toward important circuit application of squitches and the next goal is to demonstrate a ring oscillator.

- *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 full energy analysis of the stritch device was conducted. The analysis revealed that the switching energy scales with size and is comparable to the CMOS inverter. The switching energy approaches 1 aJ at a characteristic dimension of 8 nm. This result was used to design and simulate a comb-drive actuated MEMS using the CoventorWare software package, and a new MEMS fabrication process was developed. In addition, the **Stritch** team studied failures modes of previous device structures and identified the detachment of the chalcogenide monolayer from the MEM actuator and the monolayer rupture during high stress as the most important failure modes. From this analysis, a solution was developed by making an array of small holes in the chalcogenide monolayer. The holes will serve to dramatically concentrate strain around them while maintaining a relatively low global stress. The holes will also improve mechanical attachment and electrical contact of the monolayers to the MEM pads by depositing gold through the holes.

Theme III: Nanophotonics – Key Accomplishments

- *Antenna-Enhanced III-V nanoLEDs:* Period 8 has seen another milestone of this collaborative project between the **Wu**, **Yablonovitch** and **Fitzgerald** groups: The spontaneous emission enhancement in electrically-injected III-V nanoLEDs was doubled compared to last year's record high [10, 15]. Through a new antenna design, process improvements, and active layer optimization, a >200-fold increase in the spontaneous emission rate under election injection has been demonstrated. A key improvement was replacing the "bulk" InGaAsP active region with a quantum well InGaAs active region developed in the **Fitzgerald** group. The quantum well active region has improved polarization matching with the antenna-mode allowing for higher antenna enhancement.

  The **Wu** and **Fitzgerald** groups have also started work to enhance the device efficiency. P-type doping of the active region has been identified as a viable method, and a new technique was developed to p-type dope InGaAs with > 10^{19} cm^{-3} concentration by using a combination of low growth temperature and post-growth annealing to increase the activity of carbon in the lattice. In parallel, a second method to enhance the efficiency of the III-V nanoLED has been explored by reducing the non-radiative rate of the active region through reduction of surface recombination velocity. For this, the **Wu** group, with assistance by the **Javey** group, developed a diagnostic technique using time-resolved photoluminescence to measure the surface recombination velocity of pristine III-V surfaces, mimicking the nanoLED active layer. Using this technique, they have identified device fabrication steps that were undesirably increasing the surface recombination velocity. In response, a new method was developed by first depositing a thin sacrificial Al_2O_3 layer, which protects the active-region surface in device fabrication. The layer is then removed with a wet etch.

- *Chalcogenide Antenna-LEDs:* Following the first successful demonstration of electrically excited spontaneous emission from a 2D-TMDC monolayer in the last period [16], the **Wu** group, in collaboration with the **Yablonovitch** and **Javey** groups, focused on improving device design and efficiency. In period 8, the team redesigned the pulsed capacitor-based design to operate the devices in pulsed bipolar injection mode in which electrons and holes are injected at the same time. The result was a significant increase in device brightness, with 2-3 orders of magnitude higher efficiency and brightness than the initial dual-gate diodes (up to ~1 nW for ~20 um^2 devices). It should be noted that this new design is unique, and all previous studies and reports in the literature have focused on dual-gated devices. The primary benefit of pulsed operation is to prevent current decay over time due to charge trapping or other mechanisms causing threshold shift. This happens on a time-scale of seconds and can be avoided with ~1 Hz operation or higher. The team works now integrating the TMDC LED with an optical antenna, and demonstrate enhancement of spontaneous emission approaching that achieved in optically pumped devices.

- *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 on coupling light emitted from the antenna enhanced nanoLEDs into optical waveguides at high efficiencies. Using the Lumerical 3D FDTD solver, different reflector geometries were investigated. By optimizing the geometric parameters, >90 percent waveguide coupling (ratio of power radiated into the waveguide vs. total power radiated into the farfield) was achieved for the parabolic reflector into a single mode InP waveguide. Waveguide coupling >90% is comparable to the best values reported in literature for both optically and electrically pumped devices. Currently, processing steps necessary to incorporate waveguide coupling into the overall fabrication flow are developed. For this, the **Wu** group will work with the group of **Chang-Hasnain**, who recently demonstrated efficient coupling of optically-pumped emission from InP nanopillars to silicon waveguides on a silicon-on-insulator substrate. Furthermore, site-controlled growth of InP nanopillars was achieved on silicon substrate with patterned SiO2 nanomasks by low-temperature metalorganic chemical vapor deposition, compatible with silicon CMOS post-processing. This is the first site-controlled III-V nanopillar-LED emitter monolithically integrated on silicon with a silicon-transparent emission wavelength.

Theme IV: Nanomagnetics – Key Accomplishments

- *Picosecond Magnetic Switching:* In the current reporting period, the **Bokor** group in collaboration with the **Salahuddin** group completed systematic studies of the ultrafast magnetic switching effect of the ferrimagnet GdFeCo using an electrical current pulse, discovered in the last period [13]. Since conventional CMOS scaling is projected to reach transistor speeds in the range of a few picoseconds, such electrical pulses will be available on-chip and could be used to switch a magnet. In a joint collaboration with the **Wong** group, the **Bokor** and **Salahuddin** groups have thus started integration of magnetic device structures on advanced CMOS chips. A first requirement toward this goal is that ultrafast magnetic switching needs to be reached while maintaining total switching energy to be similar or lower than current state of the art switching mechanisms. Therefore, the **Bokor** group began to investigate scaling of electrical switching of GdFeCo to nanoscaled magnetic structures in order to reduce the required switching current into the micro-Ampere range. The group has succeeded in developing key fabrication processes needed to fabricate nanodots of GdFeCo down to 50 nm diameter including incorporating such dots into Hall bar structures for electrical readout.

  The **Bokor** and **Salahuddin** groups have also made progress in extending ultrafast magnetic switching from ferrimagnetic GdFeCo to other magnetic materials, most importantly to stronger magnetized ferromagnetic materials. They demonstrated a reliable method for ultrafast, helicity independent, optical single-shot toggle switching of a thin ferromagnetic layer of CoPt grown on a GdFeCo layer [17]. When this stack was irradiated by femtosecond laser pulses, reliable toggle switching of the two coupled layers was observed. Systematic studies of this process were carried out by varying the strength of the coupling between the GdFeCo layer and the CoPt layer through the use of a Pt spacer with variable thickness. It was discovered that exchange coupling between the two layers through the Pt layer is mediated by the RKKY mechanism. The ability to switch a ferromagnet by ultrafast excitation greatly expands options for design of an integrated switching and readout device.

- *Spin-Orbit Torque Switching and Magnetic Tunneling Junction Devices:* The **Salahuddin** group has studied spin-orbit torque (SOT) switching in systems with two spin-Hall metals (Ta and Pt) with opposite spin-Hall angles since such systems have shown to reduce the amount of current needed for SOT based switching. Using a technique called spin-torque-transfer-FMR (STT-FMR) it is possible to separate out different torque components, such as field-like and damping-like torque components. Analysis of the Ta-Pt bilayer structure revealed thickness dependence of the fitted data from STT-FMR spectra and it was observed that the bi-layer combination gives significantly increased damping-like torque (almost 2.5 times higher). These results show that combining spin-Hall metals with two different spin-Hall angles could provide a new way of reducing switching current.

The **Khizroev** group has continued studies of the new physics of spin-transfer torque (STT) magnetic tunneling junctions (MTJs) in the previously unexplored sub-5-nm size range for which theory predicts ultra-high magnetoresistance (MR) values. The Khizroev group developed STT junctions made of ferrimagnetic CoFe2O4 nanoparticles sandwiched between magnetic layers of traditional high-anisotropy CoFeB compositions. This device acts as a spin filter, depending on the relative orientation of the spins in the three magnetic layers. Typical dV/dI versus I curves revealed a remarkably high MR ratio above 500 and small switching currents of 0.5 nA. According to the group's theory, the reason for the significantly decreased switching current and increased spin lifetime is the dominant contribution of surface effects over the volume effects for such nanoparticle systems.

- *Computing using Magnetic Nonvolatile Devices:* This collaborative project focuses on the fabrication, design, and integration of in-memory and normally-off computing using magnetic nonvolatile devices with the goal of integrating three-terminal spin-Hall memory devices with a CMOS latch. The **Stojanovic** group evaluated several spin-based devices added to SRAM circuits. Analysis across a number of various benchmarks yielded 35 percent energy savings with this type of memory. Meanwhile, the **Wong**, **Bokor** and **Salahuddin** groups successfully patterned and tested 3-terminal spin switches with 200 percent TMR (compared to 7 percent in previous year), perpendicular magnetic anisotropy, and spin-Hall effect switching via a thick (10 nm) tantalum underlayer. In addition, successful spin-Hall effect current switching down to 250 nm wide devices was demonstrated. It should be pointed out that E^3S industry partner Applied Materials is also involved in this effort. The **Wong** group also explored the spin Hall effect in two-dimensional WSe2 materials for future versions of these devices, that can be coupled to the valley Hall effect in monolayer materials with strong spin-orbit coupling. They demonstrated that the effect is measurable at 250 K, showed control of the effect with source-drain and back-gate voltages, and calculated the spin and valley diffusion lengths.

<u>Education and Diversity Accomplishments in Period 8</u>

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^3S Professional Development Program (E^3S 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, 19 students have earned a certificate of completion.

Intended to be pathway programs, the E^3S 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 8, six REU alumni presented their research. Three TTE alumni and one E^3S REU alumni gave poster presentations at the 2017 SACNAS annual conference, two students (one TTE REU and one HBCU REU) gave a poster presentation at the 2017 NOBCChE annual conference, and one TTE REU alumni gave a poster presentation at the 2017 E^3S Symposium.

The Center has a strong record of REU program alumni going on to transfer and further their careers in graduate education. To date, 65% of undergraduate REU alumni have enrolled in a graduate program in science or engineering and 80% of community college students who did research with E^3S or E^3S affiliated faculty last year have transferred to Berkeley.

Knowledge Transfer Accomplishments in Period 8

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 for E^3S. With broad support by all of the Center's researchers and key staff personnel, 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. The Center has also continued to transfer knowledge gained from the Center's research and education activities in the areas of low-energy electronics to other applications. Technologies that are pursued by E^3S faculty with external partners include "Squitch Switches as Analog Valves", "RIE Process with Digital Etch Technology for III-V Features of High Aspect Ratios", and "Negative Capacitance Transistors".

Knowledge transfer into the Center has been actively pursued by keeping regular contacts (seminars, visits, workshops) 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 fall (October 19-20, 2017), the Center organized the Fifth Berkeley Symposium for Energy Efficient Electronic Systems. New this year was that the Berkeley Symposium joined forces with the Steep Transistors Workshop with the goal of further expanding its reach and impact. This joint event was co-sponsored by IEEE, and included keynote presentations, invited and contributed talks, as well as a poster session. This international event attracted presenters and attendees from twelve different countries and included industry presentations from Hitachi, Intel, GlobalFoundries, IMEC, CEA Leti and IRDS. A second event that the Center organized in this period, was the Second Berkeley HBCU Workshop (April 5-6, 2017) in partnership with the UCB-HBCU summer REU program, which is funded by the University of California Office of the President and is managed and operated by E^3S staff.

Lastly, in this period, the Center website has been completely re-designed and all content was updated. The link to the new website is e3s-center.berkeley.edu. The website was designed to be a major recruiting tool with a Twitter and Facebook portal, as well as a blog site. The Center for E^3S Blog Site features a variety of blog entries from Center members and is an excellent avenue to keep 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.

Center Management Changes in Period 8

The Center's leadership and management team underwent only two minor, internal changes in period 8: 1) **Lea Marlor** was promoted from education manager to associate director of education, and 2) **Kedrick Perry** (director of diversity and outreach) and **Lea Marlor** (associate director of education) were added to the Center's executive committee as regular voting members. Previously, both of them were observers (non-voting members).

The Center for E^3S External Advisory Board experienced two changes in period 8. 1) **Daniel Radack** (*Institute for Defense Analysis, IDA*) completed his full five-year term. He was thanked for his excellent service to the Center and was excused from the External Advisory Board. 2) **Thomas Theis** (*Columbia University*), who just moved after a distinguished career at IBM to Columbia University as executive director of the Columbia Nano Initiative, joined the External Advisory Board in March of this year.

Table 1.2. *Center Output in Period 8*

Publications	
Peer Reviewed Journal Publications	27
Submitted for Review	4
Peer Reviewed Conference Proceedings	29
Books and Books Chapters	1
Conference Presentations	83
Other Dissemination Activities	38
Awards and Honors	20
Ph.D. and M.S. Graduates	10
Postdoc Alumni	6
Patents and Patent Disclosures	5

Summary of Plans for Period 9

Research Plans for Period 9

Research efforts in period 9 will be guided by the Strategic Research Plan (given above). 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 dichalcogenide semiconductors, and 3) graphene nanoribbon based semiconductors.

- *III-V Nanowire TFETs:* The **del Alamo** group will conduct low-temperature studies on InGaAs vertical nanowire MOSFETs with a nanowire diameter below 10 nm, with the goal of observing single-mode 1D transport and get an insight on the subband structure of very thin vertical nanowires. In collaboration with the **Yablonovitch** group, the **del Alamo** group will study noise properties to understand the impact of a very small number of trapping defects on the device characteristics. The **del Alamo** group will also continue exploring the potential of type-II broken-gap InAs/GaSb vertical nanowire TFETs.
- *Chalcogenide TFETs:* Having successfully established a MOCVD set-up, the **Kong** group will start to explore MOCVD growth of high-quality TMDC materials. In collaboration with the **Javey** group, grown samples will be extensively characterized and properties will be compared to samples obtained by CVD and exfoliation methods. The **Javey** and **Yablonovitch** groups will continue to study defects in 2D chalcogenides and develop new “repair” methods. Results from these studies will be analyzed with respect to bandgap defect state densities. The **Javey** and the **Kong** groups will also shift their focus back to devices and developing a deeper understanding of the impact of passivation agent on the properties of various components of an FET (contact metal and dielectric layers).
- *Graphene Nanoribbon TFETs:* The **Fischer** group, guided by theoretical input of the **Louie** and **Yablonovitch** groups, will continue to develop graphene nanoribbon tunnel junction devices. The

focus will be on the development of metallic nanoribbons to serve as leads. In collaboration with the **Bokor** group, transfer techniques will be explored to test their contact resistance in FET devices. The **Louie** and **Yablonovitch** groups will further investigate the broadening of the quantum well energy levels in nanoribbon transistors using the auto-correlation function solution developed in the **Yablonovitch** group in period 8. The plan is to investigate if the lineshape in real devices can have faster decays, so that the turning ON/OFF of a double quantum well transistor could be sharper.

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 Operation:* The **Liu** and **Wu** groups will systematically investigate effects of self-assembled molecular coatings (lowering adhesion vs. increasing interfacial resistance) on properties and performances of NEM relays. The **Liu** and **Stojanovic** groups will design and fabricate relay circuits with focus on reducing voltage variations across the relays on a chip with the goal of demonstrating of sub-100 mV relay integrated circuits. The **Stojanovic** group will continue research into system integration of nanomechanical devices in so-called "edge compute" scenarios.
- *Squitch Project:* The **Squitch** team (the **Bulovic**, **Lang** and **Swager** groups) will continue work on demonstrating high-yield fabrication of four-terminal squitches and developing more complex circuits, such as be a ring oscillator. In collaboration with the **Liu** and **Wu** groups, the **Squitch** team will also explore improving the squitch by engineering electrically-active thin films from soft non-hydrophoric materials with structures that lower their tunneling barrier during actuation.
- *Stritch Project*: The **Zubia** group will team up with the **Liu**, **Javey**, and **Wu** groupsin the design of a new MEMS platform for straining 2D chalcogenide monolayers based on the energy analysis conducted on period 8. The team will also continue to address premature device failure in previous proof-of-principle stritch studies by making an array of small holes in the chalcogenides concentrate strain around them while maintaining a relatively low global stress.

Theme III – Nanophotonics: The nanophotonics team consisting of the research groups of **Ming Wu**, **Eli Yablonovitch**, **Constance Chang-Hasnain** (all *Berkeley*) and **Eugene Fitzgerald** (*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 nanoLEDs:* The **Wu**, **Yablonovitch** and **Fitzgerald** will focus on further improving the efficiency and output power of the antenna enhanced nanoLEDs by further increasing the spontaneous emission rate and minimizing surface damage from device processing. In addition, the **Fitzgerald** group will continue to optimize carbon-doping of InGaAs/InP structures for nanoLEDs, and focus on fabricating III-V single-crystalline films on Si with minimized defect-density based on the group's "remote epitaxy" technique.
- *Chalcogenide Antenna-LEDs:* The groups of **Wu**, **Yablonovitch** and **Javey** will integrate chalcogenide nanoLED structures with optical antennas with the goal of achieving spontaneous emission enhancement approaching that achieved in optically pumped devices. Different integration approaches of the optical antenna (below the TMDC with the back gate or above the TMDC using the contact metal layer) will be explored.
- *Coupling of nanoLEDs to Optical Waveguides:* The **Wu** and **Yablonovitch** groups will intensify research on coupling of the emission of antenna-enhanced nanoLEDs with optical waveguides. The

team will use the promising simulation results obtained in period 8 and develop the processing steps necessary to incorporate waveguide coupling into the overall fabrication flow. For this, the **Wu** group will also work with the **Chang-Hasnain** group, who recently demonstrated coupling of optically-pumped emission from InP nanopillars to silicon waveguides on a silicon-on-insulator substrate.

Theme IV – Nanomagnetics: The nanomagnetics team consisting of the research groups of **Jeffrey Bokor**, **Sayeef Salahuddin**, **Vladimir Stojanovic** (all *Berkeley*), **Philip Wong** (*Stanford*) and **Sakhrat Khizroev** (*FIU*) will continue research toward achieving 1) an ultra-low energy magnetic switch operating at speeds of a few picoseconds, 2) in-memory and normally-off computing using magnetic non-volatile devices, and 3) 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 **Bokor** group, in collaboration with the **Salahuddin** and **Wong** groups, will continue to focus on integrating ultrafast magnetic switches with CMOS drivers and electrical readout. The goal is to reach a switching current for ~50 nm diameter dots that is in the range of tens of microAmps, which would prove that the technology is suitable for integration with CMOS transistors. The **Bokor** group will also explore magnetic structures, which combine ultrafast heating with spin-injection. This should enable further reduction in the required switching current, and possibly allow on-demand bit-setting.
- *Spin Hall Effect and Magnetic Tunneling Junction Devices:* The **Salahuddin** group will continue to investigate heterostructure spin-Hall metals for torque enhancement by engineering bi-layer spin-Hall metals with different resistances so that the amount of spin current being generated can be controlled. In addition, the **Salahuddin** group will incorporate a 'dust layer' (<5A) of spin-Hall metals into spin-torque devices to explore whether even discontinuous layers can affect the torque. The **Khizroev** group will aim to incorporate nanoparticles with size below 1 nm into magnetic tunneling junctions. This size range is interesting since simulations showed that quantum-mechanical effects become more pronounced and the magnetoresistance ratio dramatically increases (to $\sim 10^4$).
- *Computing using Magnetic Nonvolatile Devices:* The **Wong** and **Stojanovic** groups will continue to focus on the system integration aspects of in-memory and normally-off computing using magnetic non-volatile devices. Starting with tapeout chips of CMOS latch circuits, the operation of the magnetic devices (fabricated from materials supplied by Applied Materials) with the CMOS circuits will be tested, in collaboration with the **Bokor** group. Subsequently, magnetic devices from the **Bokor** group will be directly fabricated onto the CMOS chips.

Education and Diversity Plans for Period 9

In period 9, 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. In addition, the Center's staff will seek the advice of the Education Working Group that is part of the E^3S External Advisory Board. The Education Working Group will plan to meet in the spring 2019 to discuss continuation of the programs with emphasis on funding possibilities.

Much of period 9 will be spent continuing to strengthen internship programs with recruiting emphasis on attracting women, underrepresented minorities, first-generation students, veterans, and those of varying ability/disability status. For the REU program, we plan to utilize leveraged funding from the UC Office of the President to attract students from HBCUs. Through the activities of the UCB-HBCU program (PI: **Tsu-Jae King Liu**), as well as the development of institutional ties to HBCUs, the Center strives to build a legacy of engagement in energy efficient electronics science. **Kedrick Perry** will be continuing to work with the UCB-HBCU program and its faculty to recruit qualified applicants and build strong working relationships with faculty at the HBCUs as well as expand the number of HBCUs sending students to the REU. **Tsu-Jae King Liu** will work in conjunction with **Kedrick Perry** in the planning of a workshop to host HBCU faculty in spring 2018 and further build upon these relationships.

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 include 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. Moreover, the REU selection process for summer 2018 will 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^3S 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 9

The Center will continue its broad set of knowledge transfer activities, both transfer out of the Center and transfer into the Center. With the new website in place, the Center will accelerate online knowledge transfer through use of social media and the Center for E^3S Blog Site, which will feature a continuous stream of blog entries from various Center members.

In period 9, the E^3S site on the *nanoHUB.org* website platform will go live, and will initially be used mainly for educational purposes. Highlights will include educational videos featuring Center topics as well as publication of an open-access e-book on energy efficient electronics. The e-book project has made significant progress and section on nanomechanics is close to be done.

Period 9 will also present E^3S with a special knowledge transfer opportunity as the Center will host the annual STC Directors Meeting at Berkeley. Leadership teams from all of the NSF STCs will come to Berkeley for a two-day event to share their experiences and recent activities in research, education, and diversity.

II. RESEARCH

1a. *Goals and Objectives*

The Center for E^3S was formed 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^3S 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^3S 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 Center for E^3S is organized into four research 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, leading edge CMOS technology 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 [18] projects this value to be reduced to ~40000 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—the "Landauer limit" [19-21]. Current state-of-the-art transistors lack the sensitivity to operate at powering voltages below ~0.7 V. 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, energy $>>kT$, even when the voltage is $<kT/q$.

The Center for E^3S recognized early on that for digital logic systems to approach the Landauer limit, 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 switch. Switch characteristics are parameterized by sub-threshold swing, S. Here, the value of S = 60 mV/decade is equivalent to the Boltzmann factor, and represents typical thermally activated devices.

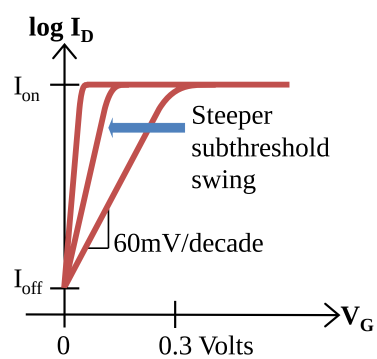


Figure 2.1. Characteristics of current (log scale) vs. voltage (linear scale) of a logic switch. In current transistors the subthreshold swing (S) is limited by the Boltzmann factor to a steepness of $\ln(10)kT/q$ = 60 mV/decade at room temperature.

From the start of the Center, E^3S set an ultimate goal for dramatically improved specifications for the proposed new switch, sub-threshold swings of ~ 1 mV/decade. Indeed, in its search for developing a new ultra-low energy switch the Center recognized early on that this switch must meet a set of key specifications:

- 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 ~1 mV/decade steepness of the subthreshold swing is necessary to achieve switching at ~10 mV of powering voltage. This is in stark contrast to the ~0.7 V required in conventional, thermally activated transistors, which require this voltage 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 ≤1 mV, good signal-to-noise ratio can be maintained even while lowering the powering voltage to 10 mV. **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 1 μm device should conduct at ~1 kΩ in the ON-state) is critical for miniaturization and integration. 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 1 mS/μm rather than 1 mA/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: 2 P5: 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*

The problems encountered in period 8 are 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.

- The most significant problem the **del Alamo** group (*MIT*) encountered on the way to obtaining single-mode sub-10 nm vertical InGaAsnanowire FETs has been the top ohmic contact. For nanowire sizes smaller than ~15 nm the top contact (for which molybdenum is used) has failed. The group switched to nickel top contacts, which is known to react in a thermal step with InGaAs to form the metallic, highly conducting phase NiInGaAs. In the process of contact formation, Ni diffuses through InGaAs and the actual electrical contact is made at the NiInGaAs/unreacted-InGaAs interface. In this way, working Ohmic contacts down to 7 nm diameters were obtained. Currently, the **del Alamo** group works on improving the contact resistance of these new contacts.
- The design and assembly of a new MOCVD setup to grow 2D chalcogenide monolayers in the **Kong** group (*MIT*) was delayed due to some technical challenges. These obstacles have been resolved and the **Kong** group has just started synthesis of monolayer chalcogenides. MOCVD grown materials will be compared to CVD grown ones in terms defect types and densities, and results will be used as a feedback to optimize the synthesis process in collaboration with the **Javey** group (*Berkeley*).
- The **Fischer** group (*Berkeley*) encountered problems in the design of molecular precursors for metallic graphene nanoribbons. While the molecules could readily be evaporated onto the growth substrate, the structure prevented the critical polymerization to form extended nanoribbons. The Fischer group has begun to redesign the structure of the molecular precursors based on theoretical calculations performed by **Steven Louie** (*Berkeley*).
- The **King Liu** and **Stojanovic** groups (both *Berkeley*) have started to implement NEMS-based switches into relay-based integrated circuits and successfully demonstrated 100 mV operation of a 2:1 multiplexer circuit comprising 2 body-biased relays. However, they also discovered that the microstructure of the poly-Si0.4Ge0.6-based devices is highly non-uniform, leading to out-of-plane deflection due to non-zero strain gradient. Since this varies from device to device, a large random voltage variation results. The **King Liu** group will explore mitigating this issue by using a thicker (stiffer) poly-Si0.4Ge0.6 film. Alternatively, the team also plans to develop a structural film with zero strain gradient; for example, using multi-target DC magnetron sputtering, which has been used to effectively and controllably grow amorphous metal thin films.
- As reported in last year's report, the nanophotonics theme has started a transition to phase out photo-receiver research due to findings by the **Yablonovitch** and **Stojanovic** groups (*Berkeley*) that a systems level solution needs to be pursued. Consequently, theme leader **Ming Wu** (*Berkeley*) decided to focus efforts in period 8 on photo-emitter research that have recently made significant progress with record-fast spontaneous emission from nanoLED devices. The **Chang-Hasnain** group (*Berkeley*) thus shifted its research focus toward the development of ultrathin layer of InP over-growth on the patch area of electrically pumped InP/InGaAs nano-LEDs to reduce surface recombination, which has been a problem due to the large surface/volume ratio and damages created by etching.
- 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^3S.

2a. *Research Thrusts in Period 8*

E³S Research Strategic Plan: The strategic research plan of the Center for E³S is given in the section, Context Statement, at the beginning of this Annual Report. The strategic plan has been guiding 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: The Center's research efforts comprise 18 research projects—all supporting the common goal of developing next-generation energy efficient electronics solutions. The collaborative nature of the Center for E³S is exemplified by the fact that 79 percent of all research projects are collaborative (i.e. are joint projects between at least two senior investigator) and 32 percent of the projects are multi-institutional, connecting senior investigators from at least two different E³S institutions.

The collaborative, multi-institutional nature of the Center for E³S is further highlighted by a special postdoc program that was established in period 7 and came to full fruition in the current funding period: The Center for E³S *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 E³S faculty members from different institutions. The new postdoc is required to spend research time at the different E³S institutions and it is fully expected that all publications coming out of these collaborative projects will have faculty co-authors from at least two different E³S institutions. In spring of this year, all four themes had their inter-institutional postdocs in place and we expect to see first impacts on the number of joint publications early in the next funding period. A brief summary of the key faculty representing the new inter-institutional collaborations facilitated by this program is given below:

- *Nanoelectronics*: Dr. **Valerio Adinolfi** is 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.
- *Nanomechanics*: Dr. **Sergio Almeida** is a postdoc shared between **Tsu-Jae King Liu** (*Berkeley*), **David Zubia** (*UTEP*), and **Junqiao Wu** (*Berkeley*) for research on the fabrication and characterization of energy-efficient low-power switches based on the latest NEMS technology developed in the nanomechanics theme. Research responsibilities include development of new nanomechanical devices, cleanroom-based device fabrication, and characterization of device switching properties.
- *Nanophotonics*: Dr. Seth Fortuna is a postdoc shared between **Ming Wu** (*Berkeley*) and **Eugene Fitzgerald** (*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.
- *Nanomagnetics*: Dr. Amal El-Ghazaly is a postdoc shared between **Jeffrey Bokor** (*Berkeley*) and **H.-S. Philip Wong** (*Stanford*) for research on design and fabrication of new magnetic devices based on ultrafast switching. The goal is to integrate GdFeCo-based magnetic switches on top of CMOS circuits built using advanced 45 nm technology chips obtained from industry foundries.

E³S Researchers: The Center for E³S has continued its collaborative research and education program, bringing together research groups from five academic institutions: UC Berkeley, MIT, Stanford, UTEP, and FIU. The faculty researchers (co-PIs) representing the research groups are:

- *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*: Dimitri Antoniadis (phased out of the center 6/30/2017), Vladimir Bulovic, Jesus del Alamo, Eugene Fitzgerald, Jing Kong, Jeffrey Lang, and Timothy Swager

- *Stanford*: H.-S. Philip Wong
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

The participation of all 21 senior researchers (faculty) within the Center's main research themes is give in the table below. As announced in last year's report, **Dimitri Antoniadis** (*MIT*) phased out of the Center by 6/30/2017. This decision was made between Prof. Antoniadis and the Center leadership as a result of the emphasis of the nanoelectronics research focus from traditional III-V semiconductors to new types of semiconductors, such as two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs). This transition in research strategy in the nanoelectronics theme came to full fruition in last funding period (end of period 6) with the addition of Profs. **Jing Kong** (*MIT*) and **Steven Louie** (*Berkeley*). 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 8

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	*Antoniadis*	*x*			
	Bulovic		x		
	del Alamo	x			
	Fitzgerald			x	
	Kong	x			
	Lang		x		
	Swager		x		
Stanford	Wong				x
UTEP	Zubia		x		
FIU	Khizroev				x

Legend: x* denotes theme leader; *Italic font* denotes phasing out of the Center

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

The goal of the nanoelectronics theme has been to develop a solid-state switch that can be actuated by ~10 milli-Volt and thus be orders-of-magnitude more energy efficient than the conventional transistor switch. Among possible alternative switching mechanisms, the tunnel switching mechanism appears to be inevitable since, with the ongoing miniaturization of devices, tunneling is an unavoidable physical effect. Tunnel transistors have been promising due to device characteristics that fulfill all three main requirements: steepness, ON/OFF ratio and conductance [1]. 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 <u>tunnel-distance modulation</u> mechanism, and not the desired <u>density-of-states modulation</u> mechanism, (also called the energy filtering mechanism"). Tunnel transistors operating on the tunnel distance mechanism show good steepness only at low current densities [2-5]. Unfortunately, tunnel distance modulation is rather ineffective at high conductance (current) density. High conductance density is needed for a competitive device since conductance density translates directly to clock speed. When averaged over both low and high current densities, a ~50 percent reduction in operating voltage might be achievable, (at best 250 mV), compared to today's conventional transistors.

Since the Center for E^3S has set its goals far below a 2-fold reduction of the operating voltage, nanoelectronics researchers at E^3S have focused on elucidating why previous attempts to design and fabricate switches operating on the preferred density-of-states modulation (or energy filtering) mechanism have failed. Guided by Theme-1 leader **Eli Yablonovitch** (*Berkeley*), researchers at Berkeley and MIT discovered that the energy filtering 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) [22], after decades of research, the defect density does not meet the requirements. For III-V interfaces the interface defect density is even worse, resulting in trap-assisted-tunneling" leakage when the switch is supposed to be "OFF". Therefore, at best, ON/OFF ratios of only ~10-100 can be achieved—far below 10^6, which is required for energy efficiency under static leakage. Therefore, even after decades of electronic material investigations, the best interface state-density materials are far from being good enough.

The main goal of the E^3S nanoelectronics research theme is to develop proper density-of-states switching tunnel transistors, exhibiting all the desired properties; high ON/OFF ratios, steep modulation, and high conductance (current) densities. The Center has realized that in order to achieve this goal, focus has to be directed at both fully understanding interfacial effects and trap-assisted tunneling and searching for new material systems with ultra-low interfacial defect states. The **del Alamo** (*MIT*) and **Yablonovitch** groups are leading efforts on understanding interfacial effects and trap-assisted tunneling, and other non-idealities of tunnel transistors. Using III-V vertical nanowire TFET structures as model systems [6,7], **del Alamo** is performing current-voltage spectroscopy of single trap nanowire tunneling 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.

Regarding the search for new semiconductor materials with ultra-low interfacial defect states the Center has focused on two different approaches:

1) Two-dimensional transition metal dichalcogenides (2D-TMDCs)
2) Graphene nanoribbons (GNRs)

2D-TMDCs are single-layer, fully covalently bonded structures with minimum surface roughness and low density of dangling bonds. Current research efforts on 2D-TMDCs are led by the **Javey** group at Berkeley and the **Kong** group at MIT with the goal to develop new bottom-up synthesis methods and further decrease the defect density of these new semiconductors.

Semiconducting GNRs, on the other hand, are chemically synthesized in an atom-by-atom fashion. Thus, their electronic properties can be precisely tailored. Heterostructures, such as quantum tunneling structures with built-in molecular quantum dots, can be designed with custom properties. The experimental part of this project is led by organic chemist **Felix Fischer** with strong theoretical electronic structure support by physicist **Steven Louie** and guidance by **Eli Yablonovitch** (all *Berkeley*).

The following provides details of period 8 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

Vertical nanowire III-V TFET structures fabricated by the **del Alamo** group (*MIT*) have proven to be excellent model systems to study the underlying physics of tunneling in semiconductors, while revealing the issue of defect assisted tunneling in the OFF-state [7]. 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. In recent years, the **del Alamo** group has developed very high aspect ratio nanometer-scale etching technology capable of reaching sub-10 nm diameters [6, 23]. This, in combination with other process innovations, including a new rapid thermal annealing (RTA) step (see below) has enabled the fabrication of InGaAs/InAs heterojunction vertical nanowire TFETs with sub-thermal subthreshold behavior and sub-10 nm diameter InGaAs vertical nanowire MOSFETs. These are the first vertical nanowire transistors of any kind on any semiconductor system with diameters below 10 nm.

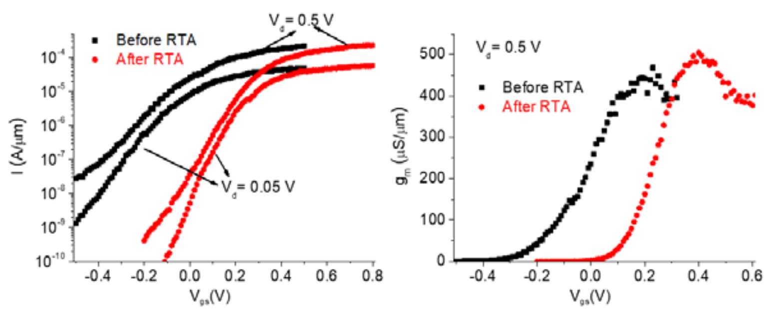


Figure 2.2. Subthreshold and transport characteristics before and after applying a final rapid thermal annealing step (350 °C for 3 minutes).

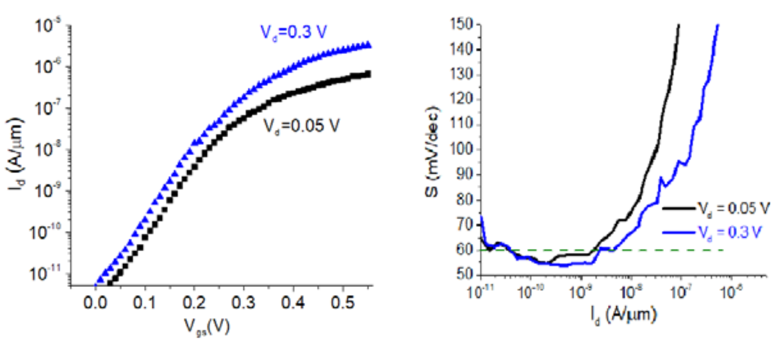


Figure 2.3. Room temperature subthreshold characteristics (transconductance and subthreshold swing) of an InGaAs/InAs heterojunction vertical nanowire TFET device after RTA treatment.

The implementation of a final rapid thermal annealing (RTA) step to improve the device characteristics of vertical nanowire transistors has proven critical to improve device characteristics. The figures below show the impact of RTA (annealing at 350 °C for 3 minutes). There is a dramatic improvement in subthreshold characteristics, a noticeable enhancement of the peak transconductance and a pronounced threshold voltage shift [24]. All this suggests a reduction in interface states at the gate oxide semiconductor interface, which bodes well for our ability to obtain future steep subthreshold devices. Using this approach, the **del Alamo** group has demonstrated top-down InGaAs/InAs heterojunction vertical nanowire TFETs with sub-thermal subthreshold behavior over two orders of magnitude of current at room temperature (see Figure 2.3), but at low current density, indicative of the tunnel distance modulation mechanism. These characteristics stem from an improved oxide- semiconductor interface as a result of the new post-process RTA step. The reduction in the interface trap density has also led to the suppression of a significant temperature dependence in the subthreshold characteristics that was observed in a previous device generation. This indicates the importance of interface trap-assisted tunneling as a dominant leakage mechanism in III-V TFETs.

The **del Alamo** group also made significant progress in fabricating vertical nanowire MOSFETs with record small diameters [25, 26]. Using the alcohol digital etch method that was developed in the last period which enables trimming of InGaAs nanowires down to below 10 nm, vertical nanowire MOSFETs with Mo contacts and a diameter of 15 nm were fabricated. These are the first devices at this dimensional range on any semiconductor system. The I-V characteristics and subthreshold behavior are shown in Figure 2.4. They demonstrate that the post fabrication RTA step has yielded outstanding subthreshold behavior with a linear subthreshold swing of 69 mV/dec, approaching the ideal value of 60 mV/dec at room temperature. The limit of 15 nm diameter is dictated by the top contact that becomes open for dimensions smaller than this one. The precise origin of this problem is not known but it seems to be due to opening of the top contact.

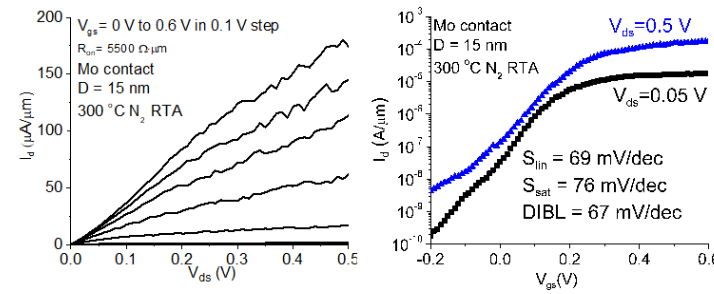


Figure 2.4. I-V characteristics and subthreshold behavior of vertical nanowire MOSFETs with 15 nm diameter nanowires, fabricated by alcohol digital etching and RTA method.

In subsequent work, the group showed that changing the top contact metallization from Mo to Ni allows to further shrink nanowire diameter and obtain working InGaAs MOSFETs with a diameter of 7 nm. This is a very significant result. To our knowledge, these are the first vertical nanowire FETs of any kind fabricated on any semiconductor system with a diameter less than 10 nm. This is a very significant achievement for the E^{3}S nanoelectronics program since InGaAs vertical nanowires FETs with with sub-10 nm nanowire dimensions can support a single 1D subband. As has been shown by the **Yablonovitch** group's modeling work, single 1D subband devices will give new insights toward the goal of elucidating the fundamental spectroscopic characteristics of tunneling energy levels. This puts E^{3}S nanoelectronics researchers in a great position to assess the ultimate current/voltage potential of tunnel switching devices.

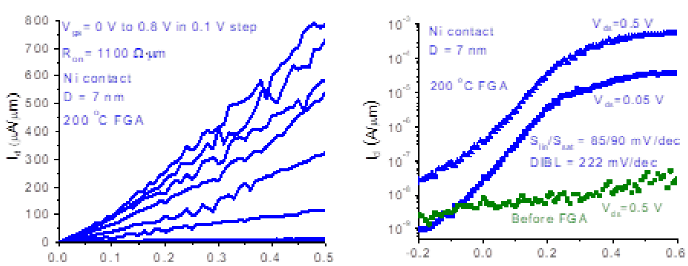


Figure 2.5. I-V characteristics and subthreshold behavior of 7 nm diameter vertical nanowire MOSFETs with Ni contacts, fabricated by alcohol digital etching and RTA method.

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 2.6. 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 2.6. 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, as shown in Figure 2.7a, it becomes difficult to turn the transistor off, and to achieve the required 10^6:1 ON/OFF ratio.

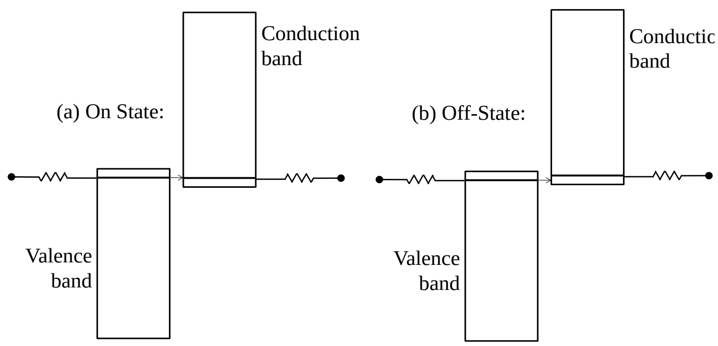


Figure 2.6. a) Exact energy alignment between the topmost valence band energy level with the bottom-most conduction band level. Exact alignment permits on-state current flow. **b)** Misalignment between the energy levels, blocking current flow. The switching characteristics depend critically on the overlap of the spectral shape of the energy levels.

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. However, 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.

The **Yablonovitch** group identified sample auto-correlation functions that behave correctly, such as $\langle\psi(0)\psi(t)\rangle \sim \exp\{-\sqrt{[b^2+(t/\tau)^2]}\}$, which is exponential at long times, but parabolic at short times, controlled by the dimensionless parabolic parameter "b". The corresponding spectral line-shape is illustrated in Figures 2.7b and c. Likewise, there are many similar temporal auto-correlation functions, which have initial temporal parabolic falloff, that all lead to correct exponential wings to the spectrum. We see this as a further elaboration 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 detailed line-shapes associated with tunnel broadening, but there are similar considerations that are needed for spontaneous light

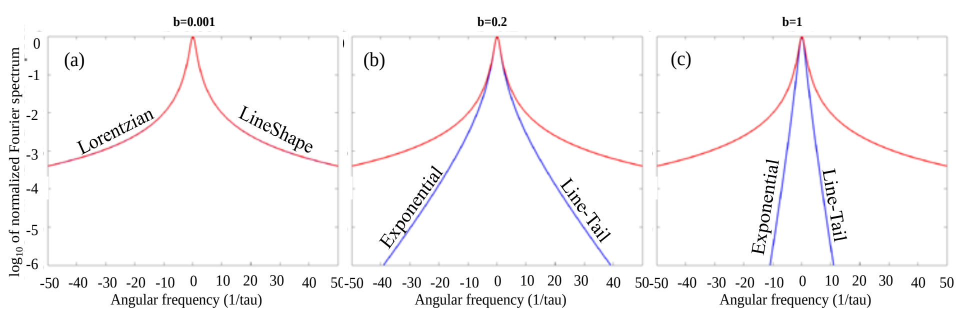


Figure 2.7. a) The conventional Lorentzian lineshape has strong spectral wings that would prevent the required 10^6:1 ON/OFF ratio. The Lorentzian arises from a perfect exponential decay of the temporal wave-function auto-correlation function. This needs to be corrected at short times leading to parabolic time decays. When Fourier transformed, in **b)** and **c)** the spectral tails become exponential, which would permit proper tunnel transistor operation. The shape is controlled by the short-time parabolic time represented by "b".

emission, and for phonon induced broadening which commonly arises in condensed matter. What all these scientific domains have in common is that the Lorentzian approximation breaks down in the spectral wings where there is insufficient experimental and theoretical knowledge.

b. Layered Chalcogenide TFETs

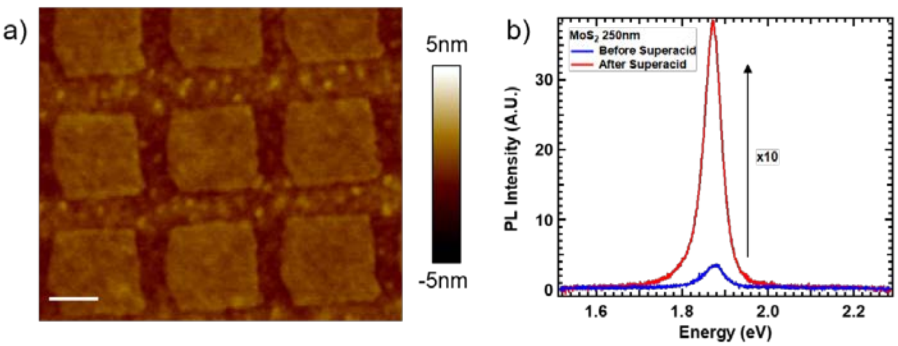


Figure 2.8. Demonstrated photoluminescence improvement of MoS2 monolayer first patterned via scanning probe lithography. Scale bar is 100nm.

In principle, two-dimensional transition metal dichalcogenides 2D-TMDCs are excellent material systems for TFETs operating on the desired energy filtering mechanism. This is owing to their completely covalently bonded structure, minimum surface roughness, and low density of dangling bonds or surface defects in their monolayers. The nanoelectronics theme of E^{3}S recognized the excellent potential of these materials early on and demonstrated practically functioning TFETs from 2D materials. As the research team around **Ali Javey** and **Eli Yablonovitch** (both *Berkeley*) came to realize, 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.

As a result, the **Javey** group moved from fabricating functioning 2D tunneling FETS (TFETs) toward 2D material engineering in order to realize better device performance through material quality improvements. A breakthrough in this context was the development of a superacid treatment method that “heals” defects in 2D chalcogenides [27, 28]. The group showed that chemically passivating the 2D materials enables them to reach their intrinsic potentials (> 95% internal fluorescence quantum yield). Furthermore, the **Javey** group in collaboration with the **Yablonovitch** group developed a method using photoluminescence lifetime and quantum yield efficiency to fully characterize and understand edge-recombination in 2D chalcogenide materials [29]. These studies revealed passivation of edge defects as one of the most important next step toward high-quality 2D-TMDC semiconductors. In response, the **Javey** group developed a technique to passivate edge defect sites of 2D materials (in addition to that of the surface) by using the same superacid method in combination with scanning probe lithography technique for edge patterning. This method was successfully applied to MoS2 monolayer materials and an enormous defect reduction (PL intensity increase) was observed (see Figure 2.8). Currently, the group is extending this approach to other chalcogenide monolayer semiconductors.

It should be emphasized that **Ali Javey’s** group is working tightly with the group of **Jing Kong** (*MIT*) and the 2D-TMDC materials used in the edge passivation project were grown by chemical vapor deposition (CVD) in the **Kong** group. In addition to extensive materials fabrication efforts, the **Kong** group has also made significant progress in materials characterization. Using scanning transmission electron microscopy (STEM) they were able to examine different types of defects in great detail, especially point defects. In collaboration with Prof. William Tisdale’s group (chemical engineering, MIT) the **Kong** group has developed an interesting method for defect characterization in 2D chalcogenide materials using phase modulated optical parametric amplification imaging (PMOPA). This technique enables the study of grain boundaries in 2D chalcogenide materials with a resolution that is close to near field techniques (see Figure 2.9).

The **Kong** and the **Javey** groups are using these various characterization tools to compare the defect types and densities in CVD and MOCVD grown materials (the MOCVD setup has just been finished and synthesis of 2D chalcogenide semiconductors has started). The **Kong** group observed that under different synthesis conditions, MoS_2 islands with different shapes were obtained. To understand the role of defects in MoS_2 electronic and optical properties, a study on defect-related behavior of different island domain shapes of MoS_2 was conducted. So far, only temperature-dependent photoluminescence and electrical conductance measurements have been done (see Figure 2.10); C-V measurements are planned to obtain defect density information.

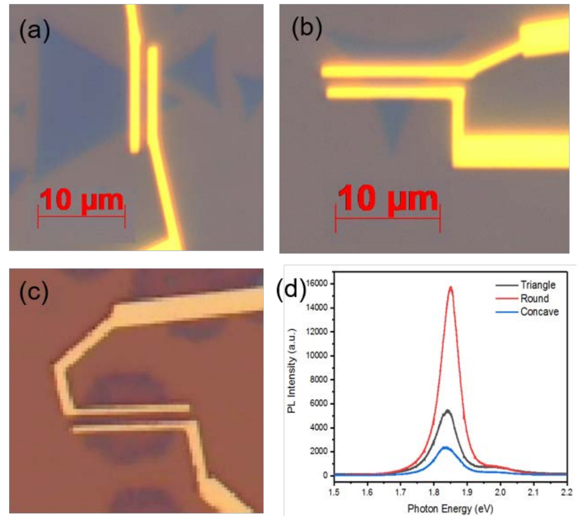


Figure 2.10. Optical microscope images of MoS2 flakes with three different shapes: triangle (a), concave (b), and round (c). d) Photoluminescence properties reveal significant differences in defect density.

Keeping the original goal of high performance TFETs in mind, as we move forward, the focus will be redirected back toward device performance and on conducting in-depth studies of the superacid's role on the electrical properties of 2D materials. If this were our only method of passivating defects, then we would need to integrate superacid treatment into the process flow.

Ic. Graphene Nanoribbon Quantum Tunneling Structures

Graphene nano-ribbons are top-down synthesized semiconducting structures that promise atomic precision and low defect density. Moreover, chemically synthesized molecular structures are subject to purification that would, segregate isomers that might produce a threshold voltage shift that would compromise the ON/OFF ratio.

The graphene nanoribbon (GNR) project has made tremendous progress since it was initiated in period 5 with the goal of 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 semiconductors quite distinct from graphene itself, which is a semimetal. The semiconducting property arises from lateral electron quantum-confinement effects in the one-dimensional nanoribbon structure. The experimental aspects of the GNR project continue to be led by the **Fischer** group (*Berkeley*) with broad theory support by the **Yablonovitch** group and the **Louie** group (*Berkeley*). The latter joined the Center at the beginning of last period

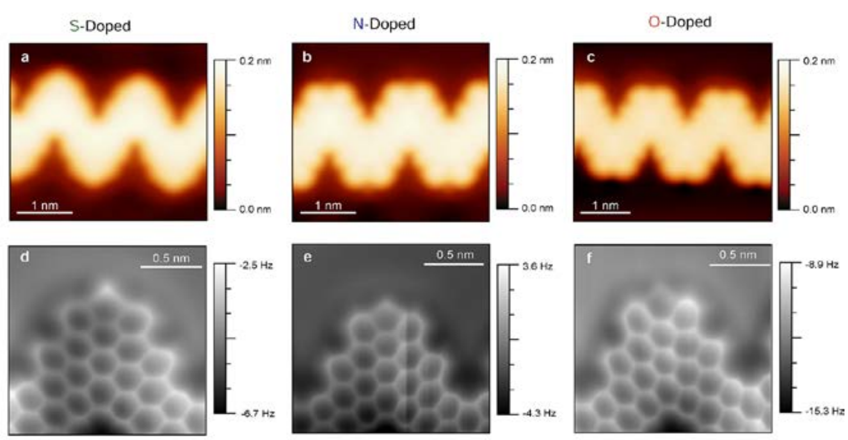


Figure 2.11. STM topographic image, and nc-AFM frequency shift image of (a, d) N-doped cGNRs (V_{bias} = 10 mV, I_t = 40 pA), (b, e) O-doped cGNRs (V_{bias} = –1.1 V, I_t = 500 pA), and (c, f) S-doped cGNRs (V_{bias} = –0.75 V, I_t = 300 pA).

and brings extensive expertise in ab initio calculations of electronic structures into the nanoelectronics theme. **Louie** is essentially using electronic structure theory to design future semiconductors.

The **Fischer** group has continued to develop bottom-up synthesis strategies for heterostructure (GNRs). In this period, particular emphasis was directed towards developing new atomically precise doping strategies. By introducing orbitally matched dopants along the edges of GNRs, tuning of both the band structure and relative position of valence and conduction band edges should be possible. Based on the **Fischer** group's expertise with bottom-up fabricated graphene nanostructures, molecular precursors were synthesized from porphyrin derivatives that are structurally compatible with a series of molecular precursors for GNRs. The placement of trigonal planar heteroatom dopants at defined positions along the convex protrusion lining the edges of cove type GNRs (cGNRs) ensures the overlap of the heteroatom lone-pairs with the extended π-system. Nitrogen-, oxygen-, and sulfur-dopant atoms were selected in this series for their varying degrees of electronegativity [30]. Samples of edge-doped cGNRs were prepared in ultra-high vacuum (UHV) on a Au(111) surface. Scanning tunneling microscopy (STM) as well as non-contact atomic force microscopy (nc-AFM) confirms the precise dopant incorporation along the GNR edges (Figure 2.11).

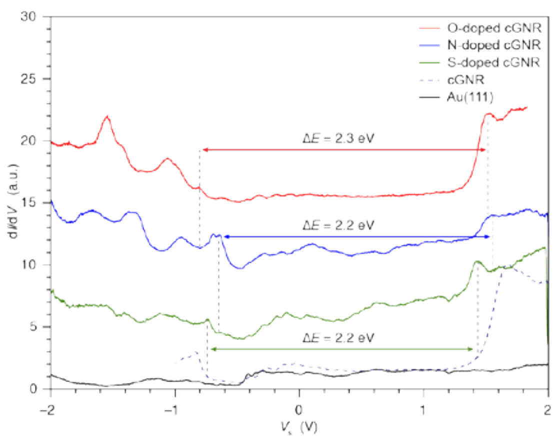


Figure 2.12. STM dI/dV point spectra of O-cGNR (red), N-cGNR (blue) S-cGNR (green), and representative Au(111) background (black). Spectra are offset vertically (O-cGNR set point: V_{bias} = –1.1 V, I_t = 50 pA; S-cGNR set point: V_{bias} = 0.05 V, I_t = 20 pA; N-cGNR set point: V_{bias} = 0.05 V, I_t = 20 pA).

Scanning tunneling spectroscopy (STS) reveals a narrowing of the band gap by ~0.2–0.3 eV per dopant atom per monomer unit when compared to unsubstituted cGNRs (Figure 2.12). The spatial distribution of valence and conduction band edge states in nitrogen-, oxygen-, and sulfur-doped cGNRs was revealed using differential conductance, dI/dV mapping. In the valence band dI/dV map of nitrogen- and sulfur-doped cGNRs, Figure 2.13, bright protrusions corresponding to the position of the dopant heteroatoms can be observed. The analogous maps for oxygen-doped cGNRs show a node at the expected position of the oxygen-atom. Differential conductance, dI/dV, maps of the conduction band edge states for nitrogen-, oxygen-, and sulfur-doped cGNRs are predominantly localized along the concave edges of the cGNRs and show a node at the position of the dopant heteroatom (Figure 2.13). The correlation of the electronic band structures of nitrogen-, oxygen-, and sulfur-doped cGNRs establishes rational and predictable structure-function relationships that are corroborated by density functional theory (DFT) calculations by **Louie**, using model Hamiltonian methods and first-principles calculations.

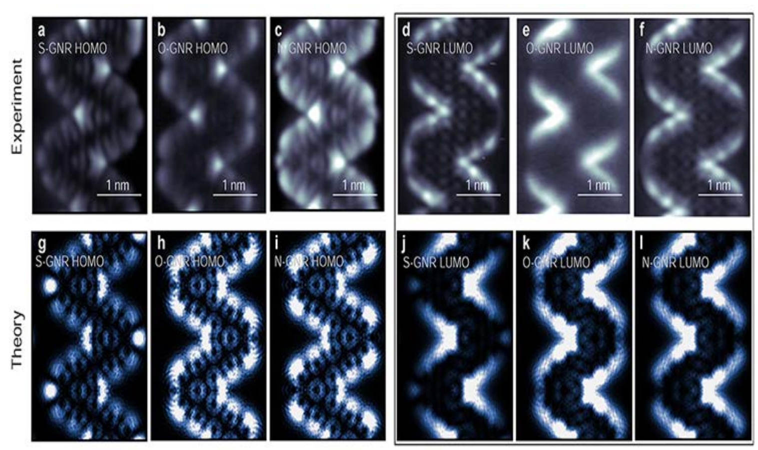


Figure 2.13. Experimental dI/dV spatial maps and calculated LDOS map of states at the valence band (VB) and the conduction band (CB) edges for (A) N-cGNRs (VB, I_t = 1.25 nA; CB, I_t = 10 nA), (B) O-cGNRs (VB, I_t = 300 pA; CB, I_t = 300 pA), and (C) S-cGNRs (VB, I_t = 1.5 nA; CB, I_t = 15 nA). Calculated LDOS is simulated at a height of 4 Å above the doped cGNR plane.

Center for Energy Efficient Electronics Science

The **Louie** group has made an interesting discovery by finding topological phases in graphene nanoribbons (GNRs). They showed that semiconducting GNRs of different width, edge and end termination (synthesizable from molecular precursors with atomic precision) belong to different electronic topological classes. The group has classified armchair GNRs of different width and end termination by topological invariant and shown that localized junction states developed between two GNRs of distinct topology may be tuned by lateral junction geometry. The topology of a GNR can be further modified by dopants, such as a periodic array of boron atoms. Using these topological effects, they designed GNR-based electronic devices with localized junction states by connecting two GNRs of distinct topology. The junction states are localized in space and form sharp energy levels in the band gap. In a superlattice consisting of segments of topological trivial and nontrivial GNRs, the junction states are stable spin centers. They could form a Heisenberg antiferromagnetic spin chain, which, when coupled to a superconducting substrate, could develop Majorana fermions at the ends of the chain. Therefore, the GNR superlattice may provide a scheme to realize Majorana physics and a platform for quantum computing [14].

More urgently needed for our project, the **Louie** group has also identified a new family of molecular precursors for GNRs featuring nitrogen dopant atoms along the backbone of an armchair GNR. This characteristic backbone doping pattern yields GNRs featuring a metallic band structure (VB/CB overlap ~ 0.1 eV). These metallic GNRs will serve as conductive leads to contact the functional element of a graphene based tunneling FET thereby effectively overcoming a key challenge in GNR based electronics, the contact resistance between a semiconducting GNR device and a macroscopic metal contact. Using these theoretical results, the **Fischer** group synthesized two model systems and explored their polymerization on a growth substrate using STM and atomic resolution nc-AFM techniques. All results showed that while the building blocks polymerized effectively on the surface the monomers never fused into the desired extended π-system characteristic for GNRs. A redesign of the monomer building block along with extensive calculations performed by **Steven Louie's** group revealed an alternative GNR architecture that features an even greater metallic overlap between VB and CB (> 3 eV). In response, the **Fischer** group successfully developed a synthesis for these new molecular precursors and initiated the first deposition and GNR growth experiments on substrates. We find this work very exciting. At any point we may discover the right molecular structure that would provide the right conducting leads to the active switching elements of future electronics.

The nanomechanics theme investigates ultra-low-voltage switches based on electro-mechanical actuation. Guided by the Center's System Integration team, strategies for leveraging zero-leakage nano-electro-mechanical (NEM) switches to enhance system performance as well as to improve energy efficiency are also investigated. Since mechanical switches conduct current when two conductive electrodes are in contact, and prevent current when these electrodes are physically separated, they can achieve immeasurably low off-state leakage (I_{OFF}) and abrupt switching behavior across a wide range of temperatures [8]. In principle, they can be operated with much lower voltage than can any type of transistor. Although they switch more slowly than do transistors, circuit design optimization to minimize the number of mechanical switching delays per function can compensate for this [31]. Therefore, NEM switches are of keen interest for digital integrated circuit applications for which energy efficiency is paramount, such as wirelessly networked devices in the emerging Internet of Things (IoT).

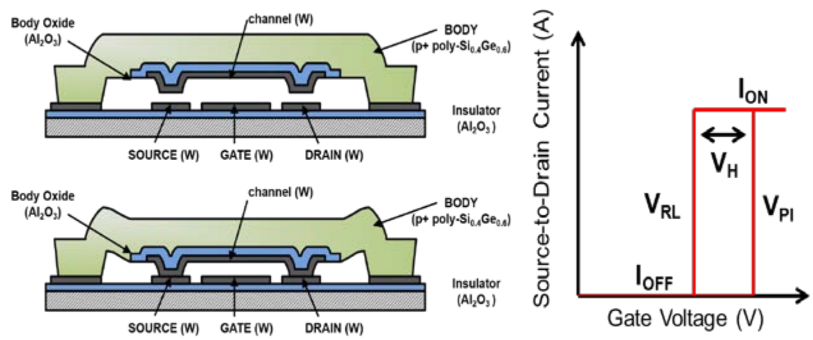


Figure 2.14. Left: Schematic illustration (cross-sectional view) of a NEM switch in the OFF state (upper) and in the ON state (lower). **Right:** Corresponding current-voltage plot, showing pull-in voltage (V_{PI}), release voltage (V_{RL}) and hysteresis voltage (V_H).

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. Therefore, the E^{3}S Center has focused on approaches to eliminate contact stiction. These include the "squitch" concept – invented at *MIT* – in which a molecular layer is sandwiched between the two conductive electrodes to prevent direct contact, and tunneling current is modulated by using electrostatic force to squeeze the molecular layer. A complementary "stritch" concept – invented at *UTEP* – uses electrostatic force to stretch (rather than squeeze) a two-dimensional molecule suspended between the two conductive electrodes, in order to induce a phase change and thereby modulate the current.

The *MIT* groups of **Vladimir Bulović**, **Jeffrey Lang** and **Timothy Swager** working on the "squitch" project have collaborated with the groups of **Tsu-Jae King Liu**, **Junqiao Wu**, and **Vladimir Stojanović** at *Berkeley* to insert molecular layers between conductive electrodes in body-biased relays (Fig. 2.14) which allow ultra-low-voltage operation to be achieved 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.

Details of period 8 research efforts in the following three areas under the nanomechanics theme are provided below.

IIa. Ultra-Low-Voltage Relay Design and Operation
IIb. Squitch: Molecular Squeeze-Switch
IIc. Stritch: 2D Chalcogenide Stretch-Switch

IIa. Ultra-Low-Voltage Relay Design and Operation

Under the guidance of theme leader **Tsu-Jae King Liu**, the E[3]S nanomechanics team has made progress in lowering the switching hysteresis voltage (V_H) of body-biased relays developed for digital IC applications [32] and shown to provide for the most energy-efficient operation [33]. In collaboration with the groups of **Vladimir Bulović**, **Jeffrey Lang**, **Timothy Swager**, and **Junqiao Wu**, an anti-stiction molecular coating process was developed for reducing V_H to enable switching with sub-50 mV gate voltage (V_G) swing [34]. However, an unwanted side effect of the anti-stiction coating of perfluorodecyltriethoxysilane (PFDTES) is an increase in sub-threshold swing, *i.e.* less abrupt switching behavior. In the current reporting period, a systematic study of the effect, mechanism, and performance of various coating molecules of different chain lengths and functional groups was conducted.

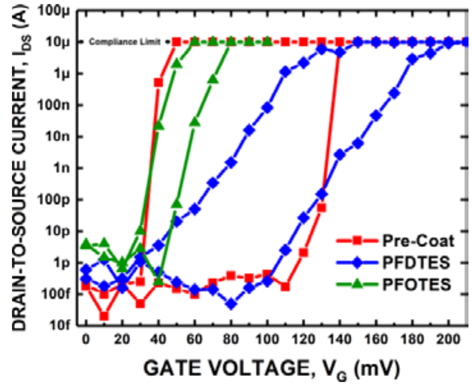


Figure 2.13. Measured I-V characteristics for body-biased relays, showing the effects of anti-stiction coatings.

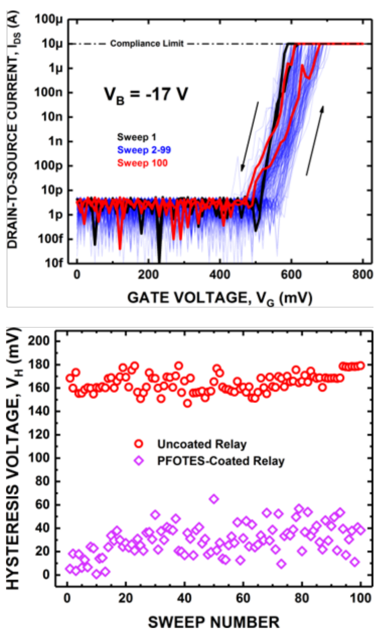


Figure 2.14. I-V characteristics (top) and evolution of V_H (bottom) for a PFOTES-coated relay operated over 100 gate voltage sweeps at a drain-to-source voltage (V_{DS}) of 1 V with body bias.

The results of this collaborative effort between *MIT* and *Berkeley* showed that molecular coatings are effective in reducing the hysteresis voltage. It should be noted that good results were obtained only by using molecular coatings with fluorinated terminal groups. Hydrogenated terminal groups were found to be ineffective for reducing contact adhesion. In general, it was found that coatings with molecules with fluorinated functional groups and a chain length of ~1.5 nm are optimal for reducing hysteresis voltage while retaining steep switching behavior. The best result was obtained using the molecule perfluorooctyltriethoxysilane (PFOTES), which reduced the hysteresis voltage from ~100 mV for a non-coated relay to ~20 mV while keeping the subthreshold swing to less than ~10 mV/decade, so that the relay was fully switched between ON and OFF states with sub-50 mV V_G swing (Figure 2.13) [35]. In addition, the low hysteresis voltage for a NEM relay coated with the PFOTES self-assembled molecular monolayer coating is stably and reproducibly maintained over hundred hot-switching cycles, as shown in Figure 2.14. Furthermore, for relays coated with PFOTES the reduced hysteresis voltage is also more stable over many switching cycles, indicative of more uniform contact properties. Finally, the **Wu** and **Liu** groups have made significant progress on understanding the current conduction mechanism in coated relays, elucidated through the study of temperature dependence of ON-state current.

The **Liu** group has identified variability in relay switching voltage (V_{PI}) as a practical challenge for demonstrating ultra-low-voltage operation of relay-based integrated circuits. Therefore, the effects of process-induced variations and device operating conditions, as well as the stability of relay switching voltages over many switching cycles, were investigated during the reporting period. A non-zero strain gradient within the structural layer was found to mitigate the effect of systematic variation in structural layer thickness but also to cause significant random variation in V_{PI} from device to device. Anti-stiction coating was found to be effective for stably reducing the magnitude and variation in V_H, facilitating reductions V_{DD}. The group has successfully demonstrated a 2:1 multiplexer circuit functioning with a supply voltage of only 100 mV (Figure 2.15).

The results of this work indicate that device-to-device variation in V_{PI} will practically limit V_{DD} reduction for relay-based integrated circuits. Because the microstructure of the poly-$Si_{0.4}Ge_{0.6}$ structural film is highly non-uniform [36], out-of-plane deflection due to non-zero strain gradient is significant and varies from device to device, resulting in large random variation in V_{PI} as seen in Figure 2.15. This issue can be mitigated by using a much thicker (stiffer) poly-$Si_{0.4}Ge_{0.6}$ film, but at a trade-off of a much larger gate-to-body voltage required to turn on the relay, *i.e.*, larger body bias voltage $|V_B|$. Alternatively, a structural film with zero strain gradient could be developed. For instance, multi-target DC magnetron sputtering has been demonstrated to effectively and controllably grow amorphous metal thin films [37, 38], a strategy that the **Liu** and **Wu** groups may pursue in the next period.

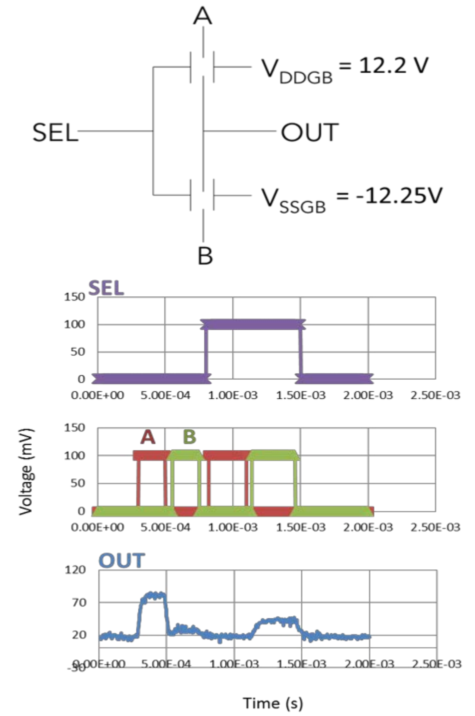


Figure 2.15. Top. Circuit diagram for a relay-based 2:1 multiplexer. **Bottom.** Measured voltage waveforms showing 100 mV operation of the circuit.

In the last period, the **Liu** group in collaboration with the **Stojanović** group (*Berkeley*) designed vertically oriented relays to be fabricated by a standard 65 nm CMOS process, using the back-end-of-line (BEOL) interconnect (metal) layers (Figure 2.16). We are delighted to report that the designed relays have been fabricated by our industry partner Texas Instruments and the devices are currently being released using dry and wet etching capabilities in the UC Berkeley Marvell Nanofabrication Laboratory. First experimental I-V results for these BEOL NEM switches are expected before the end of the current period.

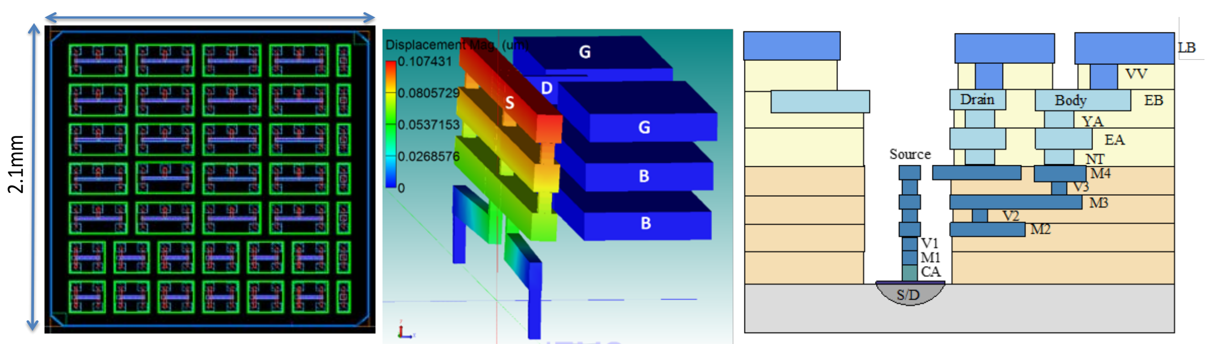


Figure 2.16. NEM switches fabricated using multiple layers in a standard BEOL process in 65 nm CMOS technology: **Left -** Mask layout. **Center -** Simulated structure of a vertically oriented body-biased relay. **Right -** Schematic cross-section after sacrificial oxide etch.

The **Stojanović** group has also started a new system integration direction by setting up a deep-learning training environment based on the Tensor Flow. This should enable evaluation of various hardware-related architectural tactics (network pruning, reduced resolution, *etc.*) and system-level evaluation of the NEM relay computing architectures. This 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. The framework developed by the **Stojanović** group has shown that pruned network layers can be obtained with high relative accuracy by starting from regular computational templates (like the block diagonal illustrated in Figure 2.17) by pseudo-randomizing the layer template matrix with permutations, and allowing the coefficients to only grow in these permuted locations during the training. This provides enough degrees of freedom for the network to converge with good accuracy, yet provides an easy way to map the resulting layer matrix to a computationally-friendly structure, especially for in-memory computing architectures that favor locality.

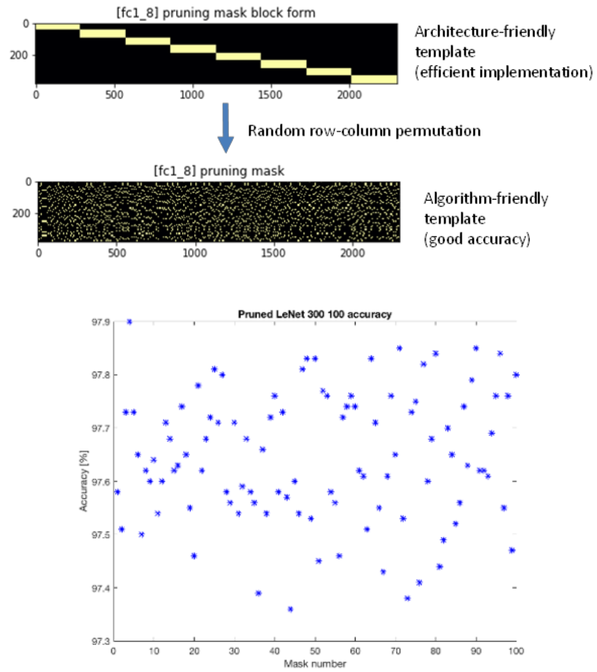


Figure 2.17. Framework developed to obtain pruned network layers with good accuracy (bottom).

IIb. Squitch: Molecular Squeeze-Switch

The research groups of **Vladimir Bulović**, **Jeffrey Lang** and **Timothy Swager** (all *MIT*) comprise the "**Squitch** group". In collaboration with the **Liu** group at *Berkeley*, this group has continued efforts to fabricate a four-terminal (body-biased) squitch device for integrated circuit demonstrations. The squitch is a NEM switch designed to conduct via tunneling through an electromechanically compressed gap containing "squeezable" molecules [9]. An illustrative four-terminal squitch is shown in Figure 2.18, 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. In this squitch, the molecular monolayer (1) defines the switch gaps, (2) provides a scaffolding to support the movable conductor and a spring to restore its position upon removal of the gate-gate voltage, and (3) prevents direct metal-metal source/drain-conductor contact thereby alleviating stiction problems. Note that the drain/source-conductor gap separation is only several nanometers. To achieve a low actuation voltage, the restoring molecular spring force must minimally over-balance the attractive van der Waals force. 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 requisite films are novel and unstudied.

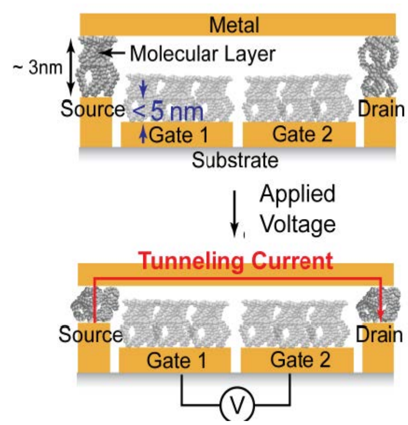


Figure 2.18. Graphic illustration of a four-terminal NEM switch employing a molecular monolayer to define and support its tunneling gap ("Squitch").

In the previous funding period, the Squitch group developed and optimized a new fabrication process flow for squitches to enable the reproducible and scalable fabrication of tunneling gaps having nanoscale smoothness, planarity and dimensional precision with high yield [39]. In the current period, the new fabrication process was used to successfully fabricate a four-terminal squitch. A micrograph of the electrodes that made up the experimental four-terminal squitch is shown in Figure 2.19. The active electrode area measured approximately 120 nm by 1200 nm. The Au electrodes exhibited sub-nanometer smoothness and planarity, having been evaporated onto an optically smooth substrate and then peeled off. The movable conductor was a Au nanorod, as opposed to a Au nanocube as described last year. The nanorod was approximately 100 nm in diameter, and 1500 nm in length. As grown, it too exhibited nanometer surface roughness and planarity. The single nanorod was moved into position using dielectrophoresis as pictured in Figure 2.20. The resistor in series with the excitation helped guarantee the dielectrophoretic placement of a single nanorod per squitch. The nanorod was supported above the electrodes by a compressible PEG-thiol self-assembled monolayer with an approximate unactuated spacing of 4 nm as shown in the micrograph above to the right.

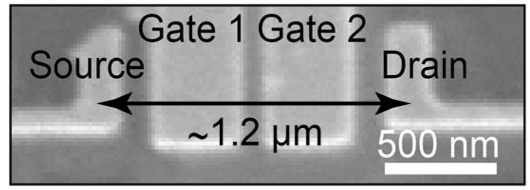


Figure 2.19. Micrograph of the electrodes fabricated for an experimental four-terminal squitch.

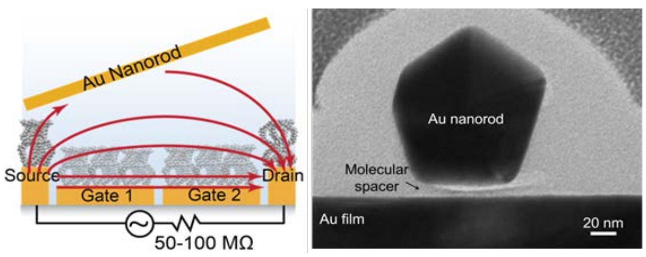


Figure 2.20. Left: Illustration of the dielectrophoretic process used to position a single Au nanorod in a four-terminal squitch. **Right:** The cross section of a completed four-terminal squitch.

The measured squitch performance is shown in the graphs of Figure 2.21. The left graph shows one upward half-sweep. It is divided into four regions: a low-voltage region (pink), a mid-voltage region (yellow), a pull-in region (dark brown), and a high-voltage region (light green). Overlaid on the half-sweep is modeled behavior based on a stationary gap (red) and a variable gap undergoing compression (green). The green model shows a much better fit to the measured data in the mid-voltage region, indicating the gap did compress with increasing gate voltage. The modeled compression indicated a 20-MPa mechanical modulus for the PEG monolayer, which is consistent with the bulk modulus reported for PEG in literature. At a gate-gate voltage of approximately 2.4 V, the squitch exhibited pull-in and a corresponding 1000-fold-plus increase in drain current. The increase is limited by power supply current compliance in the high-voltage region. These results are the first demonstration of a gated metal-molecule-metal (squitch-like) tunneling gap and current.

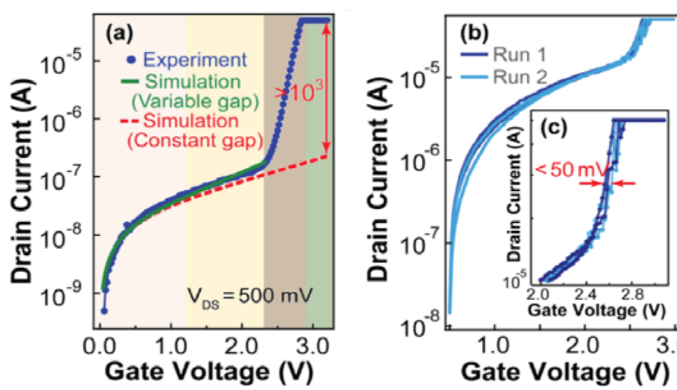


Figure 2.21. Gated drain current as a function of gate-gate voltage in a four-terminal squitch; the drain-source voltage is fixed at 500 mV. (a) Comparison of measured and modeled gated drain current in a four-terminal squitch; (b) Data from several up-down sweeps are shown. (c) Expanded view of the gated drain current as function of gate-gate voltage in a four-terminal squitch.

Furthermore, the right graph in Figure 2.21 shows drain current as a function of gate-gate voltage over several sweeps up and down; the drain-source voltage was held constant at 500 mV. The data shows the behavior to be very repeatable and absent of stiction that is common in ordinary relays. This is more clearly demonstrated in the inset with an expanded view of the pull-in and high-voltage regions. The importance of this graph is that it shows the narrow hysteresis exhibited by the squitch as it traverses a closing-opening cycle. Narrow hysteresis is important to low-energy switching. These experiments continue to demonstrate that a squitch-like structure can readily measure the mechanical modulus of thin films.

Finally, during the current funding period, the Squitch group has started with an important next step in this project by extending the new fabrication process flow to enable the fabrication of many interconnected squitches. A combined photograph and micrograph of an array of squitch electrodes is shown in Figure 2.22. The squitches can be connected by wire bonding to pads. This is a first step toward important circuit application of squitches and the next goal is to demonstrate a ring oscillator.

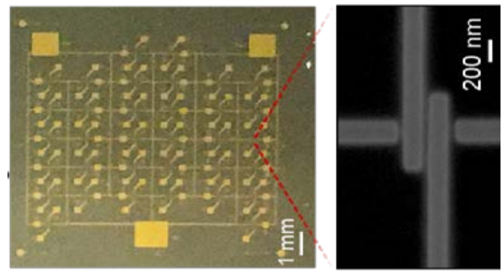


Figure 2.22 Au electrodes fabricated for an array of four-terminal squitches.

IIc. Stritch: 2D Chalcogenide Stretch-Switch

The Stritch project is led by **David Zubia**'s group (*UTEP*) in close collaboration with the **Liu**, **Javey** and **J. Wu** groups (all *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 [40]. This project studies fundamental electro-mechanical behavior of the stritch while mitigating device fabrication issues. In the past period, 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. While strain-induced electrical and optical modulation was observed, the non-linear actuation of the cantilever and the mismatch in the size of the flakes (larger) with respect to the MEM pads (smaller) created issues which limited testing due to premature device failure and low fabrication process yield. In the current period, two failures modes were identified: 1) detachment of TMD from the MEM actuator and 2) TMD rupture during high stress. Existing MEM comb-drive actuators have been used to match the size of the TMD to the pads and improve control of strain as shown in Figures 2.23a and b.

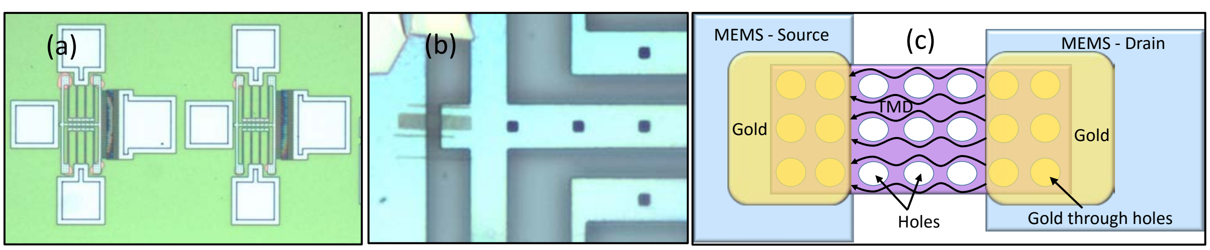


Figure 2.23. (a) MEM chevron actuators. (b) TMD transferred onto chevron actuator. (c) Array of holes in TMD to amplify strain and improve attachment.

The two failure modes mentioned above are attributed from the low deformation potential in the TMDs, which then requires high strain (~6%) to achieve sufficient ON/OFF resistance modulation (10^6). To address these electrical-mechanical challenges one idea is to make an array of small holes in the TMD as shown in Figure 2.23c. The holes will serve to dramatically concentrate strain around them while maintaining a relatively low global stress. If the array of holes is designed correctly, a highly conductive percolated path will occur allowing high ON/OFF ratios at lower global strain compared to hole-free membranes. The holes will also improve mechanical attachment and electrical contact of the TMDs to the

MEM pads. In this case, gold will be deposited through the holes to serve as mechanical anchors and electrical contacts. These device developments should lower voltage operation, increase ON/OFF ratio, improve device reliability, and increase process yield.

In addition to addressing the failure modes, the **Zubia** group performed a full energy analysis of the stritch device. This analysis showed that the switching energy scales with size and is comparable to the CMOS inverter as shown in Figure 2.24. The switching energy approaches 1 aJ at a characteristic dimension of 8 nm. This result was used to design and simulate a comb-drive actuated MEMS using the CoventorWare software package, and a new MEMS fabrication process was developed.

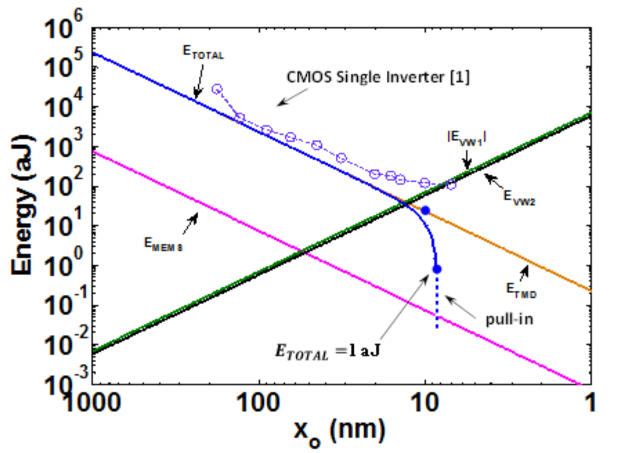


Figure 2.24. Energy analysis of the stritch device (blue line), and comparison data for CMOS inverter (blue open circles). The switching energy of MoS2 stritch device approaches 1 aJ when scaled to 8 nm.

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

The goal of the nanophotonics theme is to develop devices and systems to replace current metal wires in computers with an optical solution. On-chip optical communication between electronic gates may provide communication at unprecedented efficiency levels. In fact, nanophotonics theme researchers attempt to experimentally approach 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. This goal imposes tremendous challenges on choice of materials, nanofabrication of optical components, and their on-chip integration. Ultra-efficient and sensitive optical components need to be developed and miniaturized to be comparable to the size of transistors. Integration of optical components with waveguides is also part of the challenges of the nanophotonics research theme at E^{3}S.

To meet this goal, the Center has aimed to improve the energy efficiency and sensitivity of both the emitter and the photoreceiver. Central to the Center's nanophotonics research goals has been the demonstration that spontaneous emission from antenna-enhanced nano-LEDs can be faster and more energy efficient than the stimulated emission in lasers, the ubiquitous light source in optical communications today [10, 15]. High-speed nano-LEDs are great candidates for energy-efficient, fast and small optical emitters for on-chip optical interconnects. Major advances toward this goal have recently been achieved by demonstrating spontaneous emission enhancements of more than 300 times under optical excitation [41]. In the current period, another milestone was reached by demonstrating >200-times increase in the spontaneous emission rate under *electrical excitation*—more than doubling previously reported enhancements.

At the systems level, photoreceiver research has been of equal importance to the novel antenna-LED emitter approach. However, the E^{3}S nanophotonics researchers have found in the previous funding period 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 [11]. Thus the photo-transistor effort in the Center, which tried to combine both functions in a single device, has been eliminated. 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) 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; (3) multiple serial-to-parallel slicers that split the load on the parallel slow comparators that decide whether the bit is a 1 or a 0. As a result of these findings, the nanophotonics theme led by **Ming Wu** decided to focus period 8 efforts on the photoemitter efforts involving the **Wu**, **Yablonovitch** (both *Berkeley*) and **Fitzgerald** (*MIT*) groups, while both theoretical and experimental approaches are developed in the **Yablonovitch**, **Stojanovic** and **Chang-Hasnain** groups (all *Berkeley*) toward cavity enhancement of photo-diodes.

The following provides details of period 8 research efforts in the nanophotonics theme on:

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

IIIa. Antenna-Enhanced III-V nanoLEDs

The goal of this collaborative project between the **Wu** and **Yablonovitch** groups at Berkeley and the **Fitzgerald** group at MIT has remained to develop a III-V antenna-LED with high efficiency and multi-GHz direct modulation rate. In the last research period, a milestone was achieved by demonstrating a >100-times spontaneous emission enhancement in electrically-injected III-V antenna enhanced nanoLEDs [15, 41]. At the beginning of the current research period, the focus of the **Wu** group was directed on further enhancing spontaneous emission rates through optimization of antenna design, process improvements, and active layer optimization. As a result, a 200-fold increase in the spontaneous emission rate under election injection has been demonstrated recently (see Figure 2.25)—the best spontaneous emission enhancements

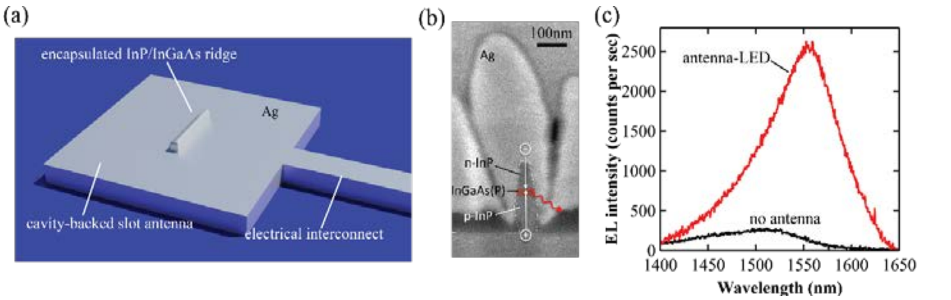


Figure 2.25. a) Schematic of electrically-injected antenna enhanced nanoLED; **b)** Cross-sectional SEM image of fabricated nanoLED; **c)** Electroluminescence (EL) spectra from nanoLED with and without antenna. Device with antenna has higher quantum efficiency.

reported for a device under electrical injection. This advancement was achieved by replacing the "bulk" InGaAsP active region with a quantum well InGaAs active region developed in the **Fitzgerald** group. The quantum well active region has improved polarization matching with the antenna-mode allowing for higher antenna enhancement. However, despite the high antenna-enhanced spontaneous emission enhancement, the efficiency of the nanoLED is lower than desired because of high non-radiative recombination at the surface of the active region.

The **Wu** and **Fitzgerald** groups identified two approaches to enhance the device efficiency: 1) Further increasing the spontaneous emission rate relative to the non-radiative rate through active region doping, and 2) reducing the non-radiative rate of the active region through reduction of surface recombination velocity. Regarding the former, the spontaneous emission rate in an LED is proportional to the product of the electron and hole density (i.e. np product). It is difficult to achieve high carrier density through carrier injection in InGaAs-based LEDs due to low conduction band offset. P-type doping the active region is an alternative method to increase the np product. However, doping InGaAs beyond 10^{19} cm^{-3} concentration is not possible with the traditional zinc MOCVD dopant precursor. Instead, the **Fitzgerald** group successfully developed a technique to p-type dope InGaAs with > 10^{19} cm^{-3} concentration by using a combination of low growth temperature and post-growth annealing to increase the activity of carbon in the lattice. After a post-growth anneal, lifetime measurements show that the recombination is dominated by Auger recombination due to the very high hole concentration (Figure 2.26).

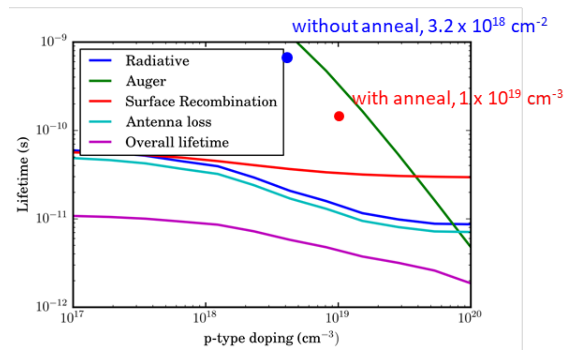


Figure 2.26. Lifetime measurements of C-doped InGaAs samples with and without annealing, showing that recombination is dominated by Auger in annealed samples.

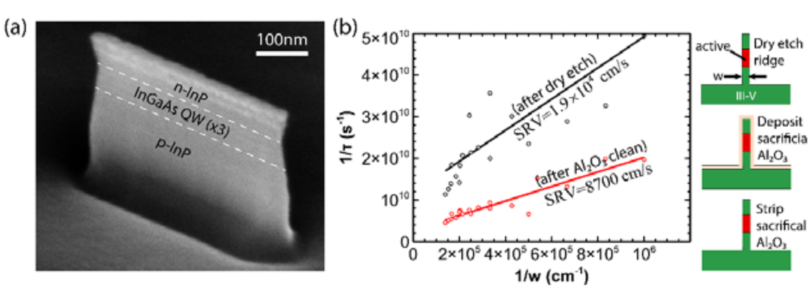


Figure 2.27. a) SEM image of one of the ridge structures used to measure the surface recombination velocity of pristine III-V surfaces; **b)** Plot of inverse lifetime versus inverse ridge width for III-V ridge before and after Al2O3 clean. Shallow slope indicates lower surface recombination velocity (SRV).

The second path to enhancing the efficiency of the III-V nanoLED is to reduce the non-radiative rate of the active region through reduction of surface recombination velocity. The efficiency of nanoLEDs is sensitive to the quality of the semiconductor surface because of high surface-to-volume ratio of the device. The Wu group, with assistance by the **Javey** group, developed a diagnostic technique using time-resolved photoluminescence to measure the surface recombination velocity of pristine III-V surfaces (see Figure 2.27a), mimicking the nanoLED active layer. Using this technique, they have identified and improved several device fabrication steps that were undesirably increasing the surface recombination velocity. Furthermore, a novel technique to reduce the surface recombination velocity of as-etched nanoscale InGaAs-based ridges below 10^4 cm/s was developed (Figure 2.27b). This was achieved by first depositing a thin sacrificial Al_2O_3 layer and then removing it with a wet etch. Prior to removal, the sacrificial Al_2O_3 can be used to protect the active region surface in device fabrication. With this reduction in surface recombination velocity, the spontaneous emission rate is predicted to surpass the non-radiative rate with a modest antenna-enhancement, allowing for high efficiency operation.

IIIb. Chalcogenide antenna-LEDs

Following the first successful demonstration of optically pumped antenna enhanced spontaneous emission from a transition metal dichalcogenide (TMDC) monolayer in period 6 [42], and light emission from TMDC monolayers by electrical charge injection in the last period, in the current period [16], the **Wu** group, in collaboration with the **Yablonovitch** and **Javey** groups, focused on improving device design and efficiency. The nanophotonics group originally started exploring chalcogenide monolayer materials for the possibility of diminished non-radiative edge recombination compared to the III-V materials. However, while the low surface recombination rates in TMDCs promises highly efficient nano-emitters, the team found that taking advantage of this in an electrically injected device involves careful consideration of the device design to limit edge recombination and to create some sort of carrier confinement required for high efficiency devices.

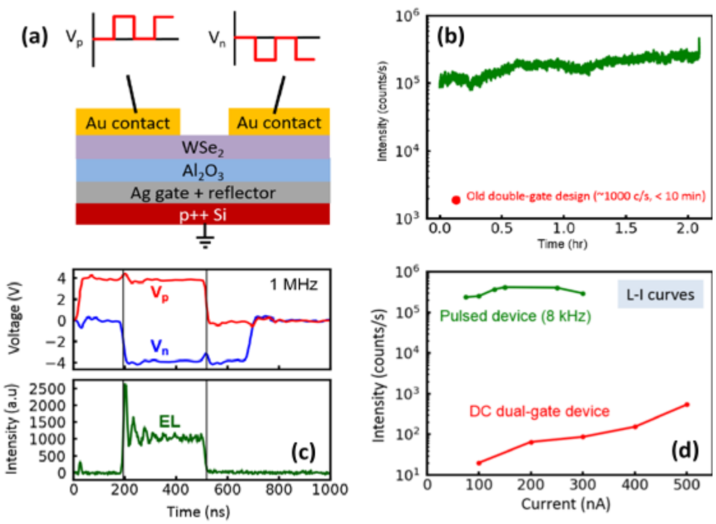


Figure 2.28. a) Device schematic and voltages applied to each terminal. **b)** Intensity over time comparison for pulsed and double-gate designs. **c)** Time-resolved electroluminescence showing emission only when pulses overlap. **d)** Comparison of intensity vs. current curves for pulsed and double-gate designs.

In period 8, the nanophotonics team redesigned the pulsed capacitor-based design, developed in the last period, to operate the devices in pulsed bipolar injection mode in which electrons and holes are injected at the same time (Figure 2.28). These new devices are the brightest seen yet, with 2-3 orders of magnitude higher efficiency and brightness than the initial dual-gate diodes (up to ~1 nW for ~20 um^2 devices). It should be noted that this new design is unique, and all previous studies and reports in the literature have focused on dual-gated devices. Time-resolved measurements for this new device design revealed that emission only occurs when both P and N voltage pulses overlap, confirming bipolar carrier injection. The primary benefit of pulsed operation is to prevent current decay over time due to charge trapping or other mechanisms causing threshold shift. This happens on a time-scale of seconds and can be avoided with ~1 Hz operation or higher. The next steps will be to integrate the TMDC LED with an optical antenna, and demonstrate enhancement of spontaneous emission approaching that achieved in optically pumped devices. In the coming period, two designs will be explored. 1) Integration of the optical antenna below the TMDC with the back gate and 2) integration of the optical antenna above the TMDC using the contact metal layer.

IIIc. Coupling of nanoLEDs to Optical Waveguides

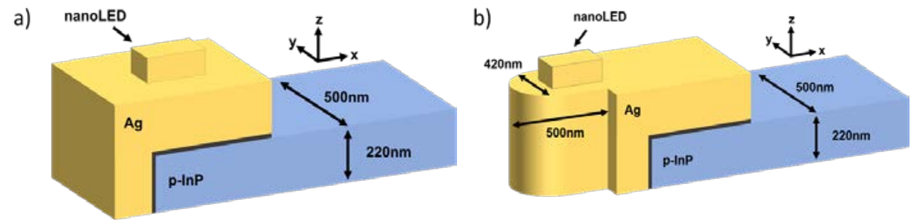


Figure 2.29. Different designs for efficient coupling of antenna enhanced nanoLED emission to an optical waveguide. **a)** Perspective view of a flat facet reflector; **b)** perspective view of a parabolic reflector.

In this funding period, the **Wu** group in collaboration with the **Yablonovitch** and **Chang-Hasnain** groups, dedicated significant efforts on the development of efficient coupling strategies of light emitted from the antenna enhanced nanoLEDs into optical waveguides. This project recognizes that nanoscale light sources for integrated optical interconnects not only need to be fast, efficient, and electrically injected, but also capable of being efficiently coupled to an optical waveguide. NanoLEDs coupled to optical antennas show great promise for small, efficient, and electrically injected light sources, but little work has been done on coupling these to waveguides. The aim of this project is to demonstrate high coupling efficiency for these nanoLEDs to single mode waveguides.

Using the Lumerical 3D FDTD solver, the group investigated two distinct coupling geometries in period 8: 1) Coupling design with a flat facet reflector (Figure 2.29a) and a parabolic reflector (Figure 2.29b). In these simulations, they achieved >90 percent waveguide coupling (the ratio of power radiated into the waveguide vs. total power radiated into the farfield) for our electrically-injected cavity backed slot antenna. The design used was using the antenna metal wrap to cancel the magnetic field propagating towards the substrate. By engineering the ground plane and the waveguide height and width, >90 percent waveguide coupling for the parabolic reflector into a single mode InP waveguide with over a 380nm 1dB bandwidth was achieved (Figure 2.30a). Waveguide coupling >90% is comparable to the best waveguide coupling reported in literature, even when compared to optically pumped antennas. Due to the promising simulation results, current efforts are underway to develop the processing steps necessary to incorporate waveguide coupling into the overall fabrication flow. For this, the Wu group will work with the group of **Chang-Hasnain**, who recently demonstrated efficient coupling of optically-pumped emission from InP nanopillars to silicon waveguides on a silicon-on-insulator substrate [43]. Furthermore, site-controlled growth of InP nanopillars was achieved on silicon substrate with patterned SiO2 nanomasks by low-temperature metalorganic chemical vapor deposition, compatible with silicon CMOS post-processing. By incorporating InGaAs multi-quantum-wells, the nanopillar emission can be tuned over a wide spectral range. This is the first site-controlled III-V nanopillar-LED emitter monolithically integrated on silicon with a silicon-transparent emission wavelength.

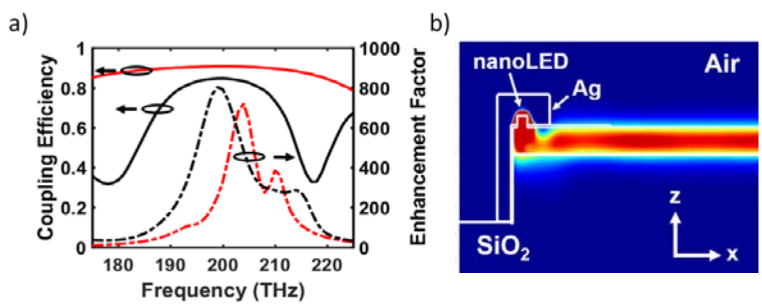


Figure 2.30. a) Waveguide coupling efficiency and enhancement. Red: Parabolic reflector Black: Flat facet reflector. **b)** Cross section of power flow.

Center for Energy Efficient Electronics Science

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

The defining goal of the nanomagnetics theme has been to develop current-driven magnetic elements for electrical communication with switching energies at the sub-femtojoule level and ultrafast switching speeds (below 10 picoseconds). In general, nanomagnetics are attractive low-energy switching candidates since the constituents tend to be metallic. Thus, the voltage requirement is low, which is compatible with the goal of low dynamic power as the digital circuits switch. In addition, the non-volatility of magnets can be used to reduce the static power losses. Despite these desirable properties of magnetics-based switching, device applications are currently hampered by 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 nanomagnetic research team comprising the groups of **Philip Wong** (*Stanford*), **Sayeef Salahuddin** (*Berkeley*), **Vladimir Stojanovic** (*Berkeley*) and **Sakhrat Khizroev** (*FIU*) addresses these challenges in magnetic switching. Jointly they take 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 [12]. Such a component can have current in/current out gain, as well as fanout. As mentioned above, a tremendous challenge in the field of magnetic switching has been the inherently low fundamental switching speed of nanomagnetic devices, including memory as well as logic. 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.

The focus of the **Bokor** group in collaboration with the **Salahuddin** group has thus been to understand the fundamental physics and the underlying switching dynamics of spintronic phenomena [44, 45]. Their efforts build 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 pulse laser [46]. Current efforts by E^{3}S nanomagnetics researchers have shown that it is possible to take advantage of this physics to achieve magnetic switching using fast electrical current pulses rather than laser pulses [45, 13]. The goal now is to reach magnetic switching speed in the range of a few to 10 picoseconds, while maintaining total switching energy to be similar or lower than current state of the art switching mechanisms. Furthermore, a joint collaboration among the **Bokor**, **Salahuddin** and **Wong** groups involves integrating magnetic device structures on advanced CMOS chips in order to test ultra-fast magnetic switching triggered by electrical pulses generated directly by CMOS circuits.

Another key achievement was the observation of strong enhancement of spin-orbit torque in heterostructure spin-Hall metals by the **Salahuddin** group. This discovery shows that combining spin-Hall metals with two different spin-Hall angles could provide a new way of reducing switching current. In the research project on fabrication and characterization of square spin-transfer torque based magnetic tunneling junction devices the **Khizroev** group succeeded in fabricating devices with sub-5-nm size. The device characteristics are currently investigated. On the circuit/system level, the **Stojanovic** group focused on evaluating the use of CMOS latches enhanced with nonvolatile spin devices in general purpose processing applications. Several spin-based devices added to latch circuits were investigated in terms of enabling non-volatile operation and saving energy during the power-gating cycles of the processor. Evaluated across a number of different benchmarks, up to 35 percent energy savings was demonstrated so far with this type of memory.

The following provides details of period 8 research efforts in the nanoelectronics theme on:

IVa. Picosecond Magnetic Switching
IVb. Spin-Orbit Torque Switching and Magnetic Tunneling Junction Devices
IVc. Computing using Magnetic Nonvolatile Devices

IVa. Picosecond Magnetic Switching

The **Bokor** group in collaboration with the **Salahuddin** group reported a breakthrough discovery in the last funding period when they demonstrated ultrafast magnetic switching of the ferrimagnet GdFeCo using an electrical current pulse [13]. Electrical pulses with duration under 10 psec were generated using an ultrafast photoconducting switch, and injected into a GdFeCo ferromagnetic resistive load. Switching of the GdFeCo load was detected using time-resolved magneto-optical Kerr effect microscopy imaging (Figure 2.31). During this funding period, the two groups completed systematic studies of this switching, carried out measurements of the electrical current pulse width and peak current amplitude, and made careful measurements of the switching dynamics [44, 45]. In addition, the **Bokor** group will also use femtosecond-laser pulse excitation of magnetic materials in an effort to get a better understanding of the underlying physics of hot electron switching.

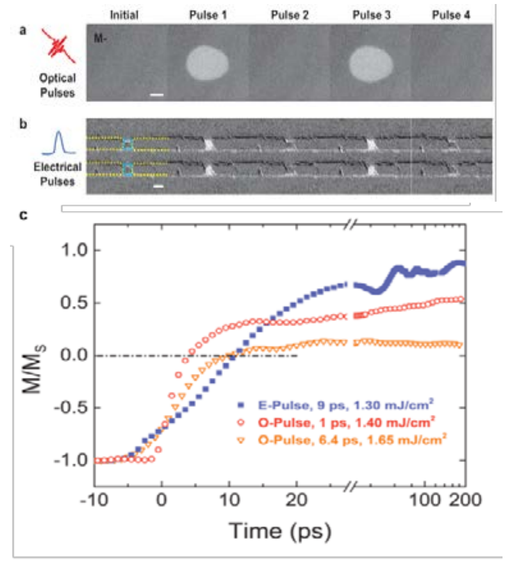


Figure 2.31. a) and **b)** Time-resolved MOKE micrographs of ultrafast (sub-10-picosecond) switching of ferrimagnetic GdFeCo switched by optical and electrical pulses. c) Magnetic switching behavior in GdFeCo as a function of pulse type and width.

Ultimately, the more practical approach 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 triggered by electrical pulses generated directly by CMOS circuits. This collaboration brings the Wong group expertise in integrating novel devices on top of CMOS and it would not have been possible without the Center because the two groups would not have become aware of each other's work and expertise otherwise. A first requirement toward this goal is that ultrafast magnetic switching needs to be reached while maintaining total switching energy to be similar or lower than current state of the art switching mechanisms. Therefore, the **Bokor** group began to investigate scaling of electrical switching of GdFeCo to nanoscaled magnetic structures in order to reduce the required switching current into the microAmps range, which would prove that the technology is suitable for integration with CMOS transistors to be used for switching and readout. This will require integrating an electrical readout into the circuit structure. So far, the group has succeeded in developing key fabrication processes needed to fabricate nanodots of GdFeCo down to 50 nm diameter including incorporating such dots into Hall bar structures for electrical readout (Figure 2.32). Maintaining good magnetic properties including perpendicular anisotropy as the size of the dots is reduced is a significant challenge.However, we now have good results down to 50 nm diamenter. Efforts are now directed to the design of suitable microwave circuits for delivering the required short electrical pulses to the readout device.

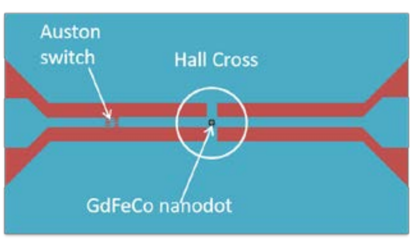


Figure 2.32. Schematic of integration of magnetic nanodots into Hall bar structures for electrical readout.

So far, only one material, GdFeCo, has been shown to switch magnetic states upon ultrafast heating by short optical or electrical pulses. This material is a ferrimagnet, and hence shows relatively weak magnetization. However, in order to engineer fully functional memory and logic devices with electrical readout, it is highly desirable to explore the possibility of extending ultrafast magnetic switching to other magnetic materials, most importantly to stronger magnetized ferromagnetic materials. Recently, the **Bokor** and **Salahuddin** groups demonstrated a reliable method for ultrafast, helicity independent, optical single-shot toggle switching of a ferromagnetic layer. A thin CoPt ferromagnetic multilayer was grown on a GdFeCo layer (Figure 2.33) [17]. When this stack was irradiated by single 55 femtosecond laser pulses, reliable toggle switching of the two coupled layers was observed. In this period, systematic studies of this process were carried out by varying the strength of the coupling between the GdFeCo layer and the CoPt layer through the use of a Pt spacer with variable thickness. Exchange coupling between the two layers through the Pt layer is mediated by the RKKY mechanism, which is known to oscillate in sign with thickness. Thus, the coupling can change from ferromagnetic to anti-ferromagnetic. Both types of coupling were observed and differences in the ultrafast dynamics for the two cases were studied. The ability to switch a ferromagnet by ultrafast excitation greatly expands options for design of an integrated switching and readout device.

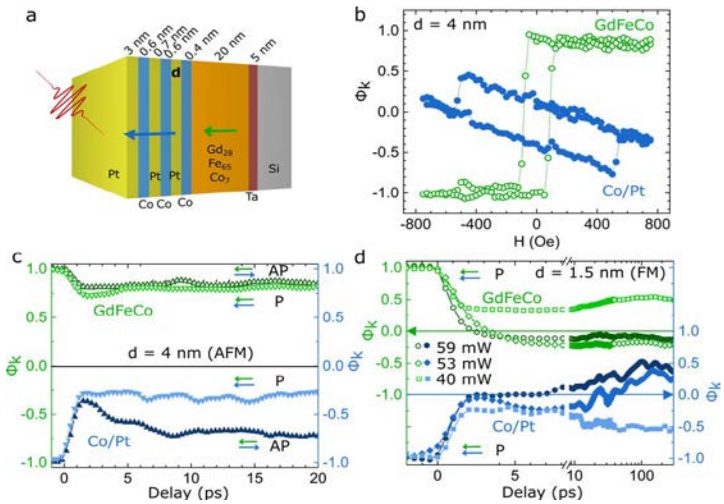


Figure 2.33. Time-resolved depth-sensitive magneto-optical measurements of laser induced dynamics. (a) GdFeCo/Co/Pt(d nm)/[Co/Pt] stack series with Pt spacer of thickness d. (b) Depth-sensitive MOKE magnetic hysteresis loops on sample d = 4 nm. (c) Depth-sensitive time-resolved demagnetization curves for anti-parallel (AP) or parallel (P) initial states of the stack d = 4 nm. Green and blue arrows represent GdFeCo and Co/Pt magnetizations, respectively. (d) Depth-sensitive demagnetization and AOS experiments at various fluences on sample d = 1.5 nm.

IVb. Spin-Orbit Torque Switching and Magnetic Tunneling Junction Devices

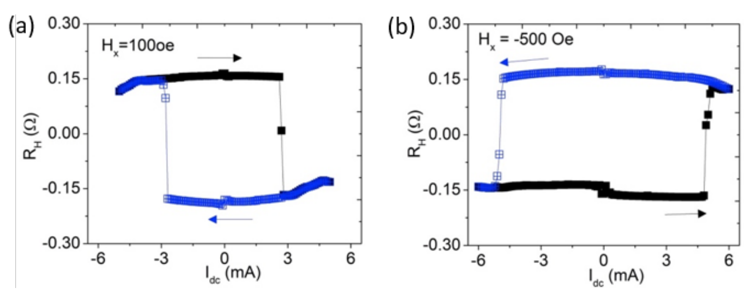


Figure 2.34. SOT switching diagram with Ta buffer layer (a) and without Ta buffer layer (b).

The main focus of the **Salahuddin** group is on devising ways to reduce current needed to switch magnets using a spin-orbit torque (SOT). The group had observed that combining two spin-Hall metals with opposite spin-Hall angles can reduce the amount of current needed for SOT based switching. For example, Figure 2.34a shows examples for a combination of a 4 nm Ta buffer underneath 5 nm Pt layer that interfaces with a CoFeB/MgO perpendicularly polarized magnet ($H_x \approx 100$ Oe; $I_{dc,max} = 6$ mA). The magnetic reversals occurred at $I_{dc} \approx +3$ mA and -3.1 mA. The SOT device without Ta-buffer layer, however, exhibited different behaviors for the I_{dc}-induced switching with significantly larger switching currents, as shown in Figure 2.34b. In the current period, the **Salahuddin** group has performed extensive research looking into these bi-layer combinations using a technique called STT-FMR. Figure 2.35a shows a typical set-up for STT FMR experiments.

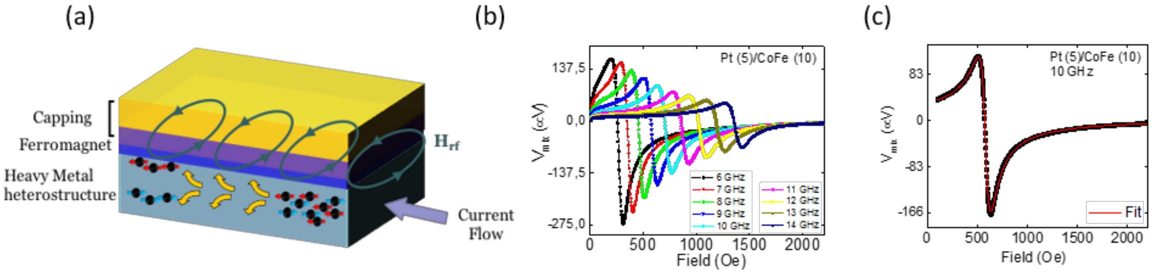
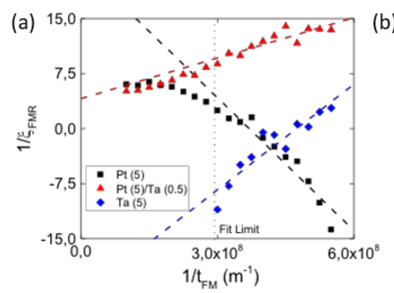


Figure 2.35. (a) Schematic set up for a STT-FMR experiment. (b) STT-FMR spectra (c) STT-FMR fit.

The essential idea is that when a RF current is applied into the heavy metal, the generated *ac* spin current can drive the magnet into resonance. By analyzing the line shape of that resonance it is possible to separate out different torque components. Figure 2.35b shows the resonance spectra and Figure 2.35c gives a fit to extract the field-like and damping-like torque components. Analysis of the Ta-Pt bilayer structure is given in Figure 2.36a, showing thickness dependence of the fitted data from STT-FMR spectra for three different stacks, one with purely Ta, one with purely Pt and one with a combination of Ta/Pt. Figure 2.36b summarizes the extracted torque values. It was observed that the bi-layer combination gives significantly increased damping-like torque (almost 2.5 times higher), in good agreement with the switching current data shown in Figure 2.34a. Note also that each point in Figure 2.36a is from a different sample, demonstrating that this trend is supported by data of a large number of samples. These results show that combining spin-Hall metals with two different spin-Hall angles could provide a new way of reducing switching current.



(b)

Stack	Spin Currents
$Ta_7/(Co_{90}Fe_{10})(t)/(MgO)_2/Ta_{1.5}$	ξ_{DL}= - 0.0572 ξ_{FL}= - 0.0169
$Ta_2/Pt_5/Ta_{0.5}/(Co_{90}Fe_{10})(t)/(MgO)_2/Ta_{1.5}$	ξ_{DL}= 0.1739 ξ_{FL}= 0.0427
$Ta_2/Pt_5/(Co_{90}Fe_{10})(t)/(MgO)_2/Ta_{1.5}$	ξ_{DL}= 0.0659 ξ_{FL}= - 0.0407

Figure 2.36. (a) Thickness dependence of the fit components from SOT-FMR spectra for three different stacks, one with purely Ta, one with purely Pt and one with a combination of Ta/Pt. (b) Torque components extracted from (a).

The **Khizroev** group has continued studies of the new physics of spin-transfer torque (STT) magnetic tunneling junctions (MTJs) in the previously unexplored sub-10-nm size range. This work is based on ab initio theoretical calculations, which have predicted that at device size ranges 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 and ultra-high magnetoresistance (MR) values should be obtained. 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 funding period, the Khizroev group developed STT junctions made of ferrimagnetic CoFe2O4 nanoparticles sandwiched between magnetic layers of traditional high-anisotropy CoFeB compositions [47]. While the measured I-V behavior confirmed the single-electron behavior of such junctions, MR values plateaued around 100 percent, mainly due to the poor uniformity of our nanostructures. In this period, the **Khizroev** group focused on improving quality and reproducibility of these double junction devices (Figure 2.37a) with a transmission electron microscopy (TEM) image of the fabricated device shown in Figure 2.37b. This device acts as a spin filter, depending on the relative orientation of the spins in the three magnetic layers. A typical dV/dI versus I curve is given in Figure 2.37c. Not only does it reveal a remarkably high MR ratio above 500, it should also be noted that the switching current (of 0.5 nA) is extremely small for such a device. According to the group’s theory, the reason for the significantly decreased switching current and increased spin lifetime is the dominant contribution of surface effects over the volume effects for such systems. The oscillating magnetic field dependence of the MR value can be explained by the presence of discrete energy states and the extreme magnetic field sensitivity of the Fermi energy.

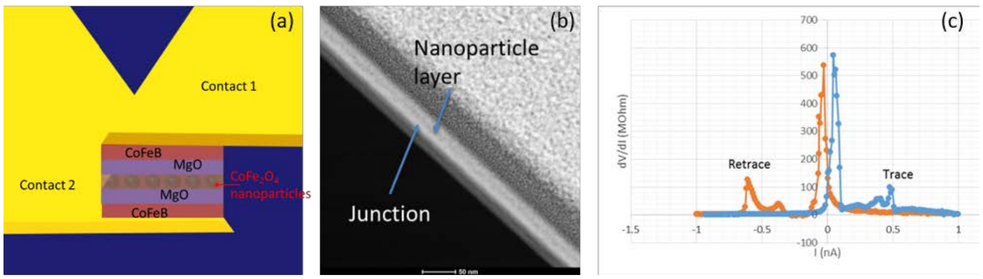


Figure 2.37. (a) Illustration and (b) TEM image of a fabricated prototype of a double junction nanoparticle-based MTJ device. (c) A typical dV/dI versus I curve.

IVc. Computing using Magnetic Nonvolatile Devices

This project is truly collaborative and inter-institutional involving the *Stanford* group of **Philip Wong** and the *Berkeley* groups of **Vladimir Stojanovic**, **Jeffrey Bokor**, and **Sayeef Salahuddin**. The project focuses on the fabrication, design, and integration of in-memory and normally-off computing using magnetic nonvolatile devices with the goal of integrating three-terminal spin-Hall memory devices with a CMOS latch. The basic idea is to reduce power by turning off large portions of the computer that are not in use. By using non-volatile memory, the shut-down part of the computer can readily be restored to its original state, once it is needed, without needing to write to or read from external storage. By distributing the memory over the circuit (memory-in-logic), we can have additional power savings due to reduced interconnect length [48].

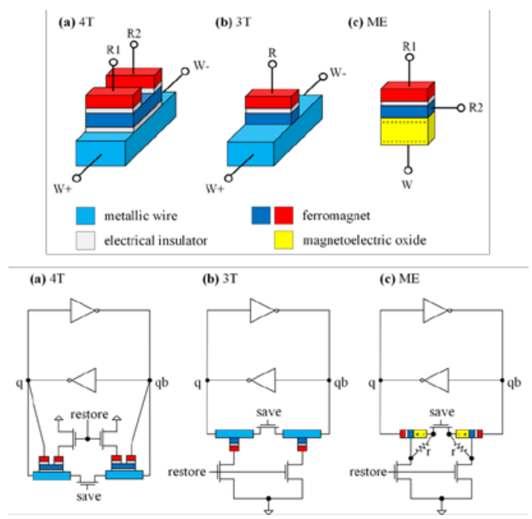


Figure 2.38. Schematics of three different spin-based devices and circuit diagrams for latch to use nonvolatility of spin switches.

The **Stojanovic** group evaluated several spin-based devices added to SRAM circuits (as illustrated in Figure 2.38) [49], to enable non-volatile operation and save energy during the power-gating cycles of the processor. During these cycles, extra power is spent both in the processor idling until the caches are flushed back to DRAM as well as in the bit transfer energy from SRAM to DRAM. Analysis across a number of various benchmarks yielded 35 percent energy savings with this type of memory.

The **Wong** group in collaboration with the **Bokor** and **Salahuddin** groups led the experimental efforts for integrating three-terminal spin-Hall memory devices with FETs to build SRAM and flip-flops, and to show that the circuits are nonvolatile and have no impact on circuit area. In the last funding period, a tapeout of the latch circuit using 130 nm CMOS and V_{dd} = 1.8 V was completed. While some delays from the foundry for return of the tapeout were encountered, it is now back and testing is underway. A microscope image of the part of this chip is shown in Figure 2.39. Modelling results for this circuit predicted that spin switches with tunnel magnetoresistance larger than 15% are needed to successfully restore the latch circuit. The tunnel magnetoresistance is defined as TMR = $(R_{AP} - R_P)/R_P$, where R_{AP} and R_P are the device resistances when the two magnetic layers have antiparallel and parallel magnetization, respectively. In this period, the research team successfully patterned and tested full 3-terminal spin switches with 200 percent TMR (compared to 7 percent in the year before), perpendicular magnetic anisotropy, and spin-Hall effect switching via a thick (10 nm) tantalum underlayer. In addition, successful spin-Hall effect current switching down to 250 nm wide devices, with switching current density ~ 1 x 10^7 A/cm^2 was demonstrated. This is a collaboration with E^{3}S industry partner Applied Materials.

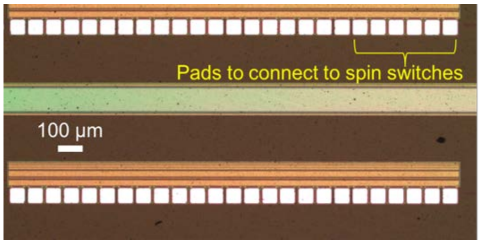


Figure 2.39. Optical image of 130 nm latch tapeout showing top-layer wire bonding pads.

In a new project, the Wong group explored the spin Hall effect in two-dimensional WSe_2 materials for future versions of these devices, that can be coupled to the valley Hall effect in monolayer materials with strong spin-orbit coupling. They demonstrated that the effect is measurable at near-room temperatures of 250 K, showed control of the effect with source-drain and back-gate voltages, and calculated the spin and valley diffusion length from the data. Figure 2.40a is a microscope image of the transistor, and Figure 2.40b is an optical map of the spin and valley Hall effect in the sample.

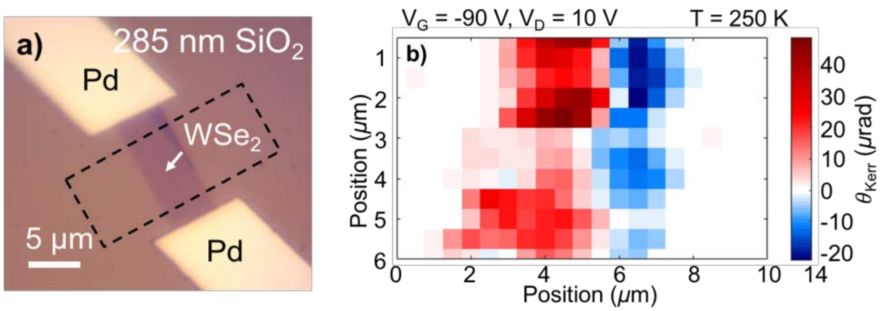


Figure 2.40. a) Microscope image of a monolayer WSe2 transistor with shown scan area and b) Kerr map of spin and valley Hall effect when the transistor is on, at 250 K.

2b. Table 2.3. Performance Against Metrics

Objective	Metric	Targets	Results						
			P 2	P 3	P 4	P 5	P 6	P 7	P 8
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)
	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)
	Publications with authors from multiple institutions	P3: 12 P4: 3 P5: 5 P6: 5 P7: 5 P8-P10: 5	0	1	1	1	3	4	4
	New joint research funding awards	P6: 1 P7: 0 P8-P10: 1	(new for P6-10)				0	3	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^3S 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 41 journal articles in this reporting period, 41 percent of these publications have two or more faculty co-authors. An area of concerns in the Center have been that the large number of multi-institutional projects (32 percent) has not been reflected in the number of joint multi-institutional journal publications (10 percent). While there is an upward trend in recent years, the Center leadership has taken steps to further improve these numbers.

The two most significant initiatives have been (1) the formation of a new postdoctoral research program, the Center for E^3S Inter-Institutional Postdoc program, and (2) an increase in available E^3S Rotation program positions. While the latter is a vehicle to enable current E^3S students and postdocs to spent mid-term (8-12 weeks) research stays at an E^3S partner institution other than their home institution, the E^3S Inter-Institutional Postdoc (IIP) program will bring four new postdocs into the Center (one per research theme). Each new postdoc must be hired into a joint position between at least two E^3S faculty members from different institutions. Furthermore, the new postdoc must spend research time at the different E^3S institutions and it is fully expected that all publications with inter-institutional postdocs as lead authors will have faculty co-authors from at least two different E^3S institutions. Three of the four new IIP positions have already been filled with the fourth to be filled early in period 8.

2c. *Research in Period 9*

Research activities in period 9 will continue to be guided by the Center for E3S Strategic Research Plan, and no major changes in the research directions of the four themes and system integration are planned in the next period. In addition, except for the planned departure of **Dimitri Antoniadis** (*MIT*), who fully phased out of the Center in the current period (6/30/2017), no further changes are planned on the senior investigator/faculty level in period 9.

Table 2.4. 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			x	
	Kong	x			
	Lang		x		
	Swager		x		
Stanford	Wong				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 9 nanoelectronics research plans is given below.

- *III-V Nanowire TFETs:* In the current period, the del Alamo group accomplished a major milestone with the successful fabrication of working InGaAs vertical nanowire MOSFETs with a nanowire diameter below 10 nm, the target diameter for a future vertical nanowire III-V CMOS technology. The goal for the coming period is to carry out extensive characterization of these devices. Low-temperature studies are planned with the goal of observing single-mode 1D transport and get an insight on the subband structure of very thin vertical nanowires. In collaboration with the **Yablonovitch** group, the **del Alamo** group will also investigated noise characteristics to understand the impact of a very small number of trapping defects on the device characteristics.

  In collaboration with IMEC (*Belgium*), the **del Alamo** group will also continue exploring the potential of type-II broken-gap InAs/GaSb VNW Tunnel FETs. Recently, they developed sub-20 nm InAs/GaSb etching capabilities and delivered arrays of vertical nanowires to IMEC for device fabrication. The heterostructures were grown at IMEC, nanowire etching was performed in the **del Alamo** group at MIT, and the rest of the process was performed at IMEC. In period 9, detailed characterization of the InAs/GaSb interface following different growth conditions will be studied, including I-V characteristics. Furthermore, the goal is to perform the entire device fabrication at MIT where process technology for VNW FETs with diameters ~10 nm has been developed meanwhile.

  In collaboration with the **Yablonovitch** group (*Berkeley*), the **del Alamo** group will continue device modeling for the development of a 3D simulation environment that solves electrostatics and quantum confinement effects self-consistently to support the design and analysis of nanowire TFETs and MOSFETs.

- *Chalcogenide TFETs:* The **Javey** group will continue to improve its successful 2D chalcogenide “repair” methods to heal defects that would be detrimental to performance of devices like TFETs, which require sharp band edges and defect-free interfaces. Using a host of optical characterization techniques established in period 8, in the coming period the focus will be on selecting out treatment schemes that can drastically decrease the unwanted edge recombination velocity in 2D chalcogenide semiconductors. The goal of this project is to reach a comprehensive investigation on both the characterization and passivation of 2D material defects existing both on the surface and the edge of these materials. This focus on improving material quality was originally motivated by the stringent requirements low energy switching requires. Having now demonstrated a qualified passivation agent for 2D material defects, the **Javey** and the **Kong** groups will now shift their focus back to devices and developing a deeper understanding of the impact of passivation agent on the electronic transport of 2D materials. Testing the impact of superacid on electrical devices will require to understand the impact of superacid on various components of an FET (contact metal and dielectric layers). The aim in period 9 is to elucidate the chemical effects and develop a deeper understanding of the treatment process.

  Having successfully established a MOCVD set-up, the **Kong** group will start to explore MOCVD growth of high-quality TMDC materials. In collaboration with the **Javey** group, grown samples will be extensively characterized and properties will be compared to samples obtained by CVD and exfoliation methods. In addition, the **Kong** group will apply novel characterization techniques to study the impact of defects in TMDC materials, including scanning gate microscopy to investigate the effect of defect on electronic transport, and capacitance measurements to map out the defect density of states close to the conduction or valence band region. Results from these studies will be analyzed in collaboration with the **Yablonovitch** group with respect to bandgap defect state densities.

- *Graphene Nanoribbon TFETs:* The **Fischer** group, guided by theoretical input of the **Louie** and **Yablonovitch** groups, will continue to explore and expand the rational bottom-up synthesis strategy for graphene nanoribbon tunnel junction devices. Particular focus in period 9 will be on the development of a bottom-up synthetic strategy towards metallic nanoribbons that are structurally compatible with semiconducting functional nanoribbon architectures designed in collaboration with the **Louie** group. Metallic graphene nanoribbons are not only an integral component of TFET architectures but address one of the most significant challenges faced in device fabrication (in collaboration with the **Bokor** group) related to contacting the semiconducting nanoribbons with metal source and drain electrodes. The performance of current single graphene nanoribbon FET devices is often dominated by the contact resistance at the metal semiconductor junction. Current work in the **Fischer** group aims at overcoming these current limitations and facilitating the charge-carrier injection at the source and drain electrodes. Initial experiments will see the preparation of heterostructures between segments of metallic and semiconducting graphene nanoribbons in an effort to study of the electronic structure at the metal/semiconductor interface using atomically resolved scanning tunneling spectroscopy. In collaboration with the **Bokor** group wet and dry transfer techniques will be explored to test the contact resistance of metallic nanoribbons in FET device architectures.

The **Louie** group in collaboration with the **Yablonovitch** group will further investigate the broadening of the quantum well energy levels that are coupled to metallic leads in tight-binding calculations of double quantum well graphene nanoribbon transistors. Currently, calculations assume the lineshape of the energy level to be Lorentzian, which has slow decay tails. The plan is to investigate if the lineshape in real devices can have faster decays, so that the turning ON/OFF of a double quantum well transistor could be sharper. In particular, the role of inhomogeneous broadening will be investigated, which might lead to a Gaussian lineshape. For this, the lineshape of a single energy level coupled to continuously densed energy levels will be studied both by analytical approach and by first-principles numerical calculations. The tunneling current will be analytically derived as a function of the tunneling electron energy in a single or double quantum well system by using non-equilibrium Green's function formalism and Kubo formalism, to obtain a general system-independent lineshape profile at strong and weak coupling limits.

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 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, squeezable molecular switches ("squitches"), and stretchable monolayer switches ("stritches"). A more detailed description of period 9 nanomechanics research plans is given below.

- *Low-Voltage Relay Design and Operation:* Based on the period 8 breakthrough of achieving NEM relays operating at ~15 mV hysteresis voltage enabled by molecular coatings, the **Liu** and **Wu** groups will systematically investigate effects of self-assembled molecular coatings on properties and performances of NEM relays in period 9. The most recent results of using vapor phase silane fluorocarbon molecules self-assembled at room temperature reduced adhesion in NEM switches and lowered hysteresis voltage from ~100 mV to ~15 mV. It was demonstrated that the amount of hysteresis reduction depends on the length of the fluorocarbon chain of the coating molecule with longer molecules (>1.5nm) reducing adhesion more than shorter molecules. However, longer molecules block the current more and lead to increased interfacial resistance, as these molecules are intrinsically insulating. Therefore, there is a tradeoff between the adhesion reduction and conduction preservation. To break the tradeoff and achieve simultaneously low adhesion and high conductance, period 9 research will focus on investigating three different coating schemes: A) Design and assembly of molecules that are both anti-stiction and electrically conductive. The design will make use of the Materials Project [https://www.materialsproject.org], which an open-source, high-throughput, ab initio materials computation platform hosted in the Lawrence Berkeley National Laboratory. B)

Mixed-assembly of anti-stiction molecules and conductive molecules. C) Development of functionalized two-dimensional materials, such as selectively fluorinated graphene, as coating material to alleviate contact adhesion and wearing without degrading conduction.

In period 8, the **Liu** and **Stojanovic** groups (both *Berkeley*) have started to implement NEMS-based switches into relay-based integrated circuits and successfully demonstrated 100 mV operation of a 2:1 multiplexer circuit comprising 2 body-biased relays. However, they also discovered that the microstructure of the poly-Si0.4Ge0.6-based devices is highly non-uniform, leading to out-of-plane deflection due to non-zero strain gradient. Since this varies from device to device, a large random voltage variation results. In the coming period, the **Liu** group will explore mitigating this issue by fabricating relays using a much thicker (stiffer) poly-$Si_{0.4}Ge_{0.6}$ structural film to reduce random out-of-plane deflection from device to device, and with smaller actuation and contact gaps to avoid very large native pull-in voltage. An alternative route will be to develop a structural film with zero strain gradient; for example, using multi-target DC magnetron sputtering, which has been used to effectively and controllably grow amorphous metal thin films. The goal is to achieve more uniform values of V_{PI} (less than 50 mV variation) across all of the relays on a chip, to enable the demonstration of sub-100 mV relay integrated circuits.

The Stojanovic group will continue research into system integration of nanomechanical 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 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 particular, integrated circuit implementations of the systems in the so-called “edge compute” scenarios will be investigated, 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. In period 9, the Stojanovic group will therefore focus on hardware macros that support efficient implementations of fully-connected and convolutional layers with enough reconfigurability to allow mapping of various popular networks. At the same time algorithmic modifications (such as permutation-based transforms/pruning and smart quantization) will be introduced to allow mapping of these highly irregular computations onto regular in-memory structures implemented with NVM relays and spin devices. Setting-up these efficient microarchitectures will enable evaluation of 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.

- *Squitch Project:* The **Squitch** team (the **Bulovic**, **Lang** and **Swager** groups at *MIT*) will continue work on improving materials and squitches, and developing more complex circuits. Group will focus on four primary objectives. The first objective is to demonstrate high-yield fabrication of four-terminal squitches. The primary challenge here is to reliably align and place a single nanorod above each set of squitch electrodes using dielectrophoresis. The second objective is to build digital circuits from many squitches. Initially wire bonding will be used to connect squitches, and then transition to back-side interconnects as squitch fabrication approaches 100% yield. The first circuit will be a ring oscillator. The third objective is to measure the dynamic performance, and explore the dynamic limits, of squitch switching. Here, the ring oscillator is enabling. The final objective is to pursue advanced thin compressible films. 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 requisite molecular thin films are novel and unstudied, and must be custom engineered. Additionally, in collaboration with the **Liu** and **Wu** groups, the **Squitch** group will explore improving the squitch 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*: Project leader **David Zubia** (*UTEP*) will continue to work closely with the **Liu**, **Javey**, and **Wu** groups at *Berkeley* in the realization of the stritch device. Recently, the group has encountered a problem with the NEMS design to mechanically stretch 2D chalcogenide monolayers. Previously designed comb drive actuators to operate the stritch device did not actuate properly. One problem was that residual stress in the films caused damage to the device during release, while another problem was that the fingers of the existing MEMS actuator were deforming with a high gate voltage. To address this major challenge, the **Zubia** group designed a new, suitable MEMS platform for straining the 2D chalcogenide monolayers based on an energy analysis of the device. In the coming period, two new MEMS platforms will be fabricated using 1) an SOI substrate and 2) SiGe-based technology. In parallel, the **Zubia** group will continue to address premature device failure in previous proof-of-principle stritch studies. Two failures modes were identified: 1) detachment of TMD from the MEMS and 2) TMD rupture during high stress. The plan is to make an array of small holes in the TMD. The holes will serve to dramatically concentrate strain around them while maintaining a relatively low global stress. If the array of holes is designed correctly, a highly conductive percolated path will occur allowing high ON/OFF ratios at lower global strain compared to hole-free membranes. The holes will also improve mechanical attachment and electrical contact of the TMDs to the MEMS pads. In this case, gold will be deposited through the holes to serve as mechanical anchors and electrical contacts. These device developments should lower voltage operation, increase ON/OFF ratio, improve device reliability, and increase process yield.

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 **Eugene Fitzgerald** (*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 9 nanophotonics research plans is given below.

- *Antenna-Enhanced III-V nanoLEDs:* The **Wu**, **Yablonovitch** and **Fitzgerald** groups plan to further improve the performance of electrically injected nano-LEDs leveraging the successes achieved in the past year. With reaching a record-high enhancement of spontaneous emission (200x) in electrical injection antenna-LED, the focus will turn to the efficiency and output power of the antenna enhanced nanoLED. As in all nanoscale devices, the surface-to-volume ratio is high in antenna-LED, particularly as the antenna gap is further scaled down. The group will pursue a two-pronged approach: 1) "Over-power" surface recombination by further increasing the spontaneous emission rate; 2) minimize surface damage from device processing by developing nanoscale fabrication processes that maintain pristine surface quality. The group will use their recently developed technique to quantify surface-recombination velocity using time-correlated single photon counting (TCSPC).

  The **Fitzgerald** group will continue to optimize InGaAs/InP structures for nanoLEDs in terms of both carbon-doping as well as for minimizing interface recombination velocity due to the carbon doping. In addition, a remote epitaxy technique will be developed to fabricate III-V single-crystalline films on Si with minimized defect-density (dislocation density < $10^4 cm^{-2}$). This is based on the group's recently discovered new epitaxy concept, termed "remote epitaxy", which can allow the growth of single-crystalline films on a graphene-coated substrate. Once monolayer graphene is inserted into the substrate-epilayer interface, crystalline information of the substrate can be transferred to the epilayer through monolayer graphene. Thus, epilayers grown on graphene can be free of dislocation if remote epitaxy is performed for the lattice-matched system like homoepitaxy and the resulting epilayers can be easily released from graphene surface owing to weak interaction. Lattice-matched InGaAs will be grown on graphene/InP substrates via remote epitaxy and InGaAs will be transfer on Si substrates. Graphene films will be grown or transferred on InP substrates and the team will develop the remote epitaxy and transfer on 2-inch wafers. The reusability of the InP wafer will be tested.

- *Chalcogenide Antenna-LEDs:* With the period 8 accomplishment of the new pulsed bipolar injection mode device with 2-3 orders of magnitude higher LED emission efficiency and brightness, the team composed of the groups of **Wu**, **Yablonovitch** and **Javey** is now in a great position to integrate chalcogenide nanoLED structures with optical antennas. The goal is to achieve spontaneous emission enhancement approaching that achieved in optically pumped devices. The optical antenna can be integrated below the TMDC with the back gate, or above the TMDC using the contact metal layer. Both approaches will be explored and the most promising route will be down-selected. The team will also design experiments to elucidate the physical mechanism behind the observation that slightly offset bipolar pulsed injection produces the highest output power. The optimum waveform for electrical modulation will be identified.

  Recently, the team has also started to investigate solution-based chalcogenide semiconductor quantum dots as an alternative active-region for the nanoLED. Chalcogenide colloidal quantum dots have several advantages such as high quantum yield and narrow emission spectrum. Furthermore, they can be deposited on arbitrary substrates. Proof-of-concept experiments will begin in period 9.

- *Coupling of nanoLEDs to Optical Waveguides:* The **Wu** and **Yablonovitch** will intensify research on this new project of efficient coupling of the emission of antenna enhanced nanoLEDs to optical waveguides, which is of great importance for integrated optical interconnects. The team will use the promising simulation results obtained in period 8 and develop the processing steps necessary to incorporate waveguide coupling into the overall fabrication flow. First steps will be to optimize waveguide coupling structures, and fabricate initial systems based on an optically pumped structure on a glass substrate. Results of these first experimental systems will then be used to move to integrated on-chip LEDs, and further to electrically pumped systems. For this, the **Wu** group will also work with the **Chang-Hasnain** group, who recently demonstrated coupling of optically-pumped emission from InP nanopillars to silicon waveguides on a silicon-on-insulator substrate.

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

The nanomagnetics team consisting of the research groups of **Jeffrey Bokor**, **Sayeef Salahuddin**, **Vladimir Stojanovic** (all *Berkeley*), **Philip Wong** (*Stanford*) and **Sakhrat Khizroev** (*FIU*) will continue research toward achieving 1) an ultra-low energy magnetic switch operating at speeds of a few picoseconds, 2) in-memory and normally-off computing using magnetic non-volatile devices, and 3) energy-efficient magnetic switching using spin-orbit torque and nanometer-sized spin torque transfer magnetic tunneling junction devices. A more detailed description of period 9 nanomagnetics research plans is given below.

- *Picosecond Magnetic Switching and Integration with CMOS:* The **Bokor** group, in collaboration with the **Salahuddin**, **Stojanovic** and **Wong** groups, will continue to focus on making further progress towards demonstrating an ultrafast magnetic memory including integrated switching using CMOS drivers and electrical readout. First step is to validate scaling principles for the switching current required as the magnetic dot size is scaled down to nanoscale. The goal is to reach a switching current for ~50 nm diameter dots that is in the range of tens of microAmps, which would prove that the technology is suitable for integration with CMOS transistors to be used for switching and readout.

This will first be done using the Auston switch technology in the **Bokor** group. However, since nanoscale magnetic dots will be fabricated, they will be too small to readout optically. Therefore, electrical readout mechanisms need to be developed. First, the group will use anomalous Hall effect, but later in the project they will move to GMR readout, and ultimately to MTJ readout. The **Bokor** group will also explore design magnetic structures, which combine ultrafast heating with spin-injection. This should enable further reduction in the required switching current, and possibly allow on-demand bit-setting in contrast to the current toggle switching that they have observed in GdFeCo.

- *Spin Hall Effect and Magnetic Tunneling Junction Devices:* With the remarkable enhancement of the torque observed in the heterostructure spin Hall metals in this current period, the **Salahuddin** group will continue to investigate this system in order to better understand the source of this enhancement. One hypothesis is that interaction between spin currents of oppositely polarized spin could enhance the amount of spin current absorbed by the magnet. To test this hypothesis, in period 9, bi-layer spin Hall metals will be engineered with different resistances so that the amount of spin current being generated can be controlled. In addition, the **Salahuddin** group will investigate heterostructures for which a 'dust layer' (<5A) of spin Hall metals will be incorporated into the interface between magnet and a traditional spin Hall metals like Pt. The idea is to explore whether even such a layer, which is not expected to be a continuous layer, can affect the torques.

  In period 9, the **Khizroev** group will continue to exploit the new physics of sub-5-nm magnetic tunneling junction devices. After the successful demonstration of devices with incorporated ~2 nm $CoFe_2O_4$ nanoparticles, the group will work on further reducing the nanoparticle size below 1 nm. This size range is interesting since simulations showed that quantum-mechanical effects become more pronounced and the magnetoresistance ratio further dramatically increases (to $\sim 10^4$). Simulations also showed that the probability of switching to the highest resistance state substantially increases when the magnetic field is increased above 0.3 T. This is reminiscent of typical spin telegraph noise, indicating a bi-stable state of the system. This behavior is most likely the result of the extremely small size of the nanoparticles (< 1 nm) and the dominance of surface over volume effects. Here, electron spins become relatively isolated from their environment, including typical room temperature noise. As a result, spins stored in such nanoparticles can remain stable for at least several years even at room temperature, despite their small size.

- *Computing using Magnetic Nonvolatile Devices:* The **Wong** and **Stojanovic** groups will continue to focus on the system integration aspects of in-memory and normally-off computing using magnetic non-volatile devices. With the successful design, in the last period, of latch circuits capable of incorporating magnetic devices with CMOS for a non-volatile memory architecture, they will now seek to test the integration of the two together. Starting with tapeout chips of CMOS latch circuits, the operation of the magnetic devices (fabricated from materials supplied by Applied Materials) with the CMOS circuits will be tested, in collaboration with the **Bokor** group. Subsequently, magnetic devices from the **Bokor** group will be directly fabricated onto the CMOS chips. The next step will be to redesign the CMOS layout to enable direct integration of spin Hall memory devices on CMOS. Finally, the team will move to 2D FETs to enable more flexibility in future monolithic 3D integration as envisioned in the N3XT architecture. The spin Hall devices will be fabricated in the **Bokor** and **Salahuddin** groups, the Si CMOS is provided by a foundry to which the Wong group has access to, and the 2D FETs will be fabricated in collaboration with the **Javey** group.

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 2017 E^3S 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^3S training	Yearly beginning in Period 3	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50% Period 6: 15% Period 7: 30% Period 8: 40%
	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: 50 Period 7: 75 Period 8: 110
	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% Period 8: 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% Period 4: 80% Period 5: 80% Period 6: 85%

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			Period 7: 85% Period 8: 85%
	Pre-college students who pursue a bachelor's degree in science and engineering	Yearly beginning in Period 3	Period 3: Baseline Period 4: 70% Period 5: 70% Period 6: 80% Period 7: 80% Period 8: 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% Period 6: 30% Period 7: 30% Period 8: 30%

In the E^{3}S 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^{3}S Leadership Program.

1c. *Problems Encountered*

Much of the efforts in period 8 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 8, the Center graduated nine graduate students and six postdocs. In addition, ten undergraduates who were research interns with the Center, either through one of the REU programs (E^{3}S REU or ETERN) also received their baccalaureate. To date, E^{3}S has graduated 165 graduates (62 undergraduates, 60 graduates, and 43 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^{3}S Director, **Eli Yablonovitch** has been teaching biennially a graduate level course on low energy electronics with a strong focus on E^{3}S topics and perspectives. The course was not offered Period 8, and will again be offered in Period 9.

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 8, 32 graduate students and eleven 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, 19 students have earned a certificate of completion, of these, two were awarded in period 8. More than half, 46 (58%) of the E^3S students participated in a training area in period 8, with 29 (37%) 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 8, 25 students and postdocs received training in these area. In addition, in period 8, the Center offered a workshop on scientific communication that was attended by 22 students and postdocs.

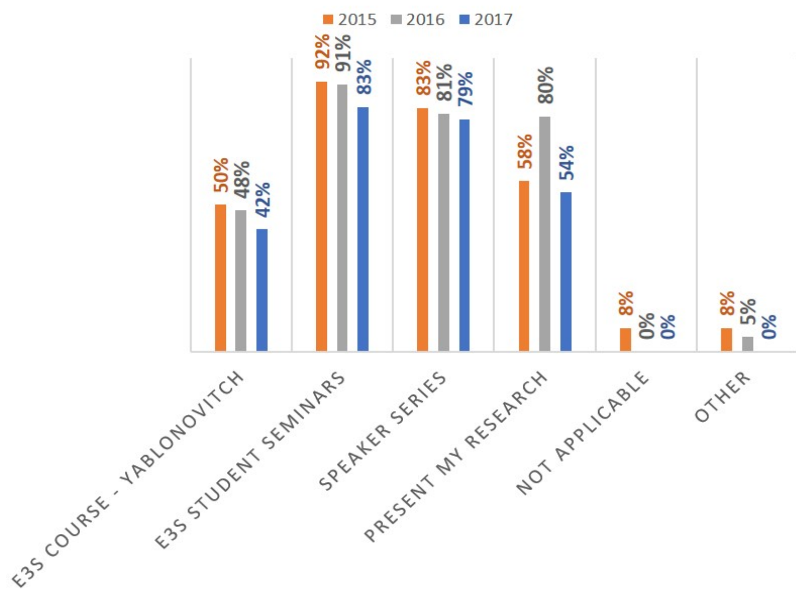

Figure 3.1. Graduate students and postdocs indicated the Center's educational activities are sharpening their understanding of low energy consumption device science and technology.

The recent 2017 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).

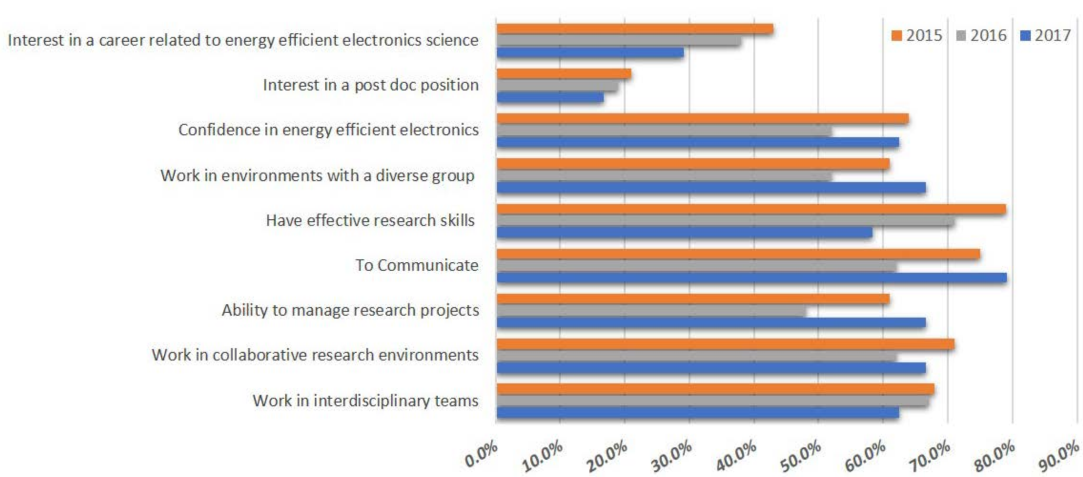

Figure 3.2. Graduate Students and postdocs indicated that the Center has positively impacted their professional development and interests.

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 8, there were two ETERNs at UCB and UTEP.

The Center also manages three REU programs for undergraduates from 4-year institutions and community colleges. Six community college students and 18 undergraduates from 4-year institutions were hosted in E^{3}S or E^{3}S affiliated research groups at MIT, UTEP, and Berkeley. In alignment with the Center's focus community college education, three E^{3}S faculty supported the professional development of four community college faculty in period 8 with the goal of enhancing STEM classroom instructions. One community college professor developed teaching materials for an introductory engineering course. Two community college professors have introduced a lecture about their topics in a general chemistry course and an introduction to data science course. The remaining community college instructor is continuing to develop her curriculum based on the six weeks of curriculum development she did over the summer.

The following sections provide details supporting the above summary of the state of education in period 8.

2a. Internal Educational Activities

The internal educational activities that were initiated in previous reporting periods continued in period 8. 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 – 308 Undergraduate Students: 65 Berkeley, 3 MIT Graduate Students: 84 Berkeley, 2 MIT, 2 UTEP Postdocs: 52 Berkeley, 9 MIT, 3 Stanford, 5 FIU

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 8 is expected to conclude with 14 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 C.

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 – 53 Graduate Students: 16 Berkeley, 4 MIT, 2 FIU, 2 UTEP Postdocs: 5 Berkeley, 3 MIT, 1 FIU

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 19 posters at the 2017 Annual Retreat presented by 16 graduate students (12 Berkeley, 1 FIU, 1 MIT, 2 UTEP), 4 postdocs (4 Berkeley). For a list of posters, please see Appendix J.

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 – 8 Graduate Students: 6 Berkeley Postdocs: 2 Berkeley

This period, 8 students and postdocs were given the opportunity to present their research to the external advisory board.

Table 3.5.

Activity Name	Fifth 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 – 22 Graduate Students: 13 Berkeley, 2 UTEP, 2 MIT Postdocs: 4 Berkeley, 1 MIT

In August, the Center hosted its 6th Annual Student and Postdoc Retreat for graduate students and postdocs. Graduate students and postdocs spent most of the day in the science communication workshop. Additional topics discussed outside of the workshop were the E3S 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 UCB, 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 8, 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, 75% (12) have completed a four-year degree in an E3S related major. Six are currently enrolled in graduate school (for STEM and all at E3S institutions). Cumulatively, 25% (4) are underrepresented minorities and 30% (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: 1 FIU, 1 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) worked in Prof. **Tsu-Jae Liu**'s lab under the guidance of postdoc, **Sergio Almeida** in the fall of period 8. His project worked on the 2D stritch. **Mark Stone** (FIU) worked in Prof. **Jeffrey Bokor**'s lab in the summer of period 8 with postdoc **Amal El-Ghazaly** on a project using AFM/MFM/STM characterization, TEM/SEM imaging/spectroscopy, VSM and focused MOKE magnetometry.

2b. Professional Development Activities

The students and postdocs of the Center for E^3S 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^3S Leadership Certificate that students receive after completing enough areas in the Professional Development Program (E^3S 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^3S Professional Development Program (E^3S PDP)
Led by	**Lea Marlor** (Berkeley)
Intended Audience	All Graduate Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 29 Graduate Students: 15 Berkeley, 2 MIT, 1 FIU, 1 UTEP Postdocs: 5 Berkeley, 2 MIT, 2 Stanford, 1 UTEP

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^3S PDP is a framework to ensure a student or postdoc receives well-rounded professional experiences (Appendix D). 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, nineteen students have earned a certificate of completion, of these, 2 were awarded in Period 8. Approximately half, 46 (53%) of the E^3S students started a training area by the end of Period 8, and 29 (33%) have completed at least one training area by the end of Period 8.

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: 13 Berkeley

	Postdocs: 12 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	Science Communication Training
Led by	**Lea Marlor** (Berkeley)
Intended Audience	All Graduate Student and Postdocs
Approx. Number of Attendees (if appl.)	Total – 22 Graduate Students: 13 Berkeley, 2 UTEP, 2 MIT Postdocs: 4 Berkeley, 1 MIT

Additional opportunities for leadership experiences for graduate students and postdocs were provided at this year's annual retreat in form of a Science Communication workshop. The training, conducted by Dr. Aditi Risbud, discussed how to cater science talks for specific audiences, how to put together an elevator pitch, and gave the students an opportunity to practice these skills. Each student, who attended this workshop, also presented an elevator pitch at this year's annual retreat.

Table 3.11.

Activity Name	REU Selection Committee
Led by	**Kedrick Perry** (Berkeley)
Intended Audience	All Graduate Student and Postdocs
Approx. Number of Attendees (if appl.)	Total – 10 Graduate Students: 5 Berkeley, 2 FIU, 1 MIT, 1 UTEP Postdocs: 1 Berkeley/UTEP

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 3.12.

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 – 15 Graduate Students: 12 Berkeley Postdocs: 3 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 a 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 8, 15 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 3.13.

Activity Name	E^3S Teacher Fellows Program
Led by	**Lea Marlor** (Berkeley)
Intended Audience	Community College Professors
Approx. Number of Attendees (if appl.)	Total: 4

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 8, the Center hosted four 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 four E^3S visiting community college faculty are described below.

- **Angela Gee**, a faculty member in the Department of Biology 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 introductory biology courses that is currently being implemented.
- **Leonard Filane**, a physics and math instructor at College of Marin, conducted six 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 summer and he continues to work with Berkeley faculty members to get the course accredited for students to transfer to a four-year school.
- **Bill Schwarz**, a computer science instructor at Cañada College conducted his 8-week project in Prof. **Vladimir Stojanovic**'s lab, and was mentored by postdoc **Ranko Sredojevic**. **Hui Sun Kim**, a chemistry instructor at Laney College, worked in Prof. **Ming Wu**'s lab, and was mentored by graduate student **Seth Fortuna**. These two remaining professors have implemented their projects into an Introduction to Data Structures course and a General Chemistry course, respectively.

Table 3.14.

Activity Name	E^3S 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 6, each theme leader will have produced an outline for their section. Graduate students and postdocs have worked to create the content for the book in period 8, and currently Theme 2 has created a first draft for its section.

Table 3.15.

Activity Name	Cal Day
Led by	**Aine Minihane** (Berkeley)
Intended Audience	The San Francisco Bay Area Community
Approx. Number of Attendees (if appl.)	Total- 3 Graduate Students: 3 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 eight 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 400 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 8 targets. The table below displays these data and future metrics to measure education success.

Table 3.16.

Objective	Metric	Targets	Results						
			P 2	P 3	P 4	P 5	P 6	P 7	P 8
Education	Center graduates completed E^{3}S training	P2: Baseline	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)	5 (36%)
		P3: 50%							
		P4: 50%							
		P5: 50%							
		P6: 15%							
		P7: 30%							
		P8: 40%							
		P9: 50%							
		P10: 15%							
		P6: 50	(new for P6-10)				0	0	0

	Students accessing online courses of the Center	P7: 75 P8: 110 P9: 170 P10: 250							
	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%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P2: Baseline P3: 5% P4: 80% P5: 80% P6: 85% P7: 85% P8-P10: 85%	n/a	3 (100%)	6 (100%)	7 (100%)	6 (100%)	4 (80%)	4 (60%)
	Pre-college students who pursue a bachelor's degree in science and engineering	P3: Baseline P4: 70% P5: 70% P6: 80% P7: 80% P8-P10: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)	180 (47%)
	Students and postdocs serving in leadership roles in the Center	Period 2: Baseline P3: 15% P4: 20% P5: 25% P6: 30% P7: 30% P8: 30% P9: 20% P10:15%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)	14 (16%)

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 9

Much of period 9 will be spent in continuing the established education programs and continuing in the creation and development of the Center's Education legacy. The E-book is in the process of being drafted, and outside funding is also being applied for.

IV. KNOWLEDGE TRANSFER

1a. *Goals and Objectives*

The mission and vision of the Center for E^{3}S as a Science and Technology Center is to foster groundbreaking new science discoveries and fertilize new technologies. Knowledge transfer is thus at the heart of E^{3}S and the Center 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. Therefore, the Center for E3S regards knowledge transfer as a two-way street in its mission to develop novel, highly efficient electronic technologies and to engage stakeholders of various science and engineering disciplines and at different educational levels in participating in these new opportunities.

Within the Center for E^{3}S, 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^{3}S 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 Period 6: 25 Period 7: 25 Period 8: 30
	External citations of publications *(cumulative)*	Yearly	Period 3: 10 Period 5: 100 Period 6: 25% yearly increase Period 7: 25% yearly increase Period 8: 25% yearly increase
	Talks at peer-reviewed conferences *(added in Period 6)*	Yearly	Period 6: 12 Period 7: 12 Period 8: 15
	Center sponsored symposia & workshops	Bi-annually	Period 2: baseline Period 3: 0 Period 4: 1 Period 5: 0

			Period 6: 2 Period 7: 1 Period 8: 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 Period 6: 3 Period 7: 3 Period 8: 4
	Patents Disclosures/Provisional	Yearly	Period 3: 3 Period 4: 3 Period 5: 5 Period 6: 2 Period 7: 2 Period 8: 3
	Patent Application Filed/Granted	Yearly	Period 4: 0 Period 5: 3 Period 6: 1 Period 7: 2 Period 8: 2
	Center's alumni into relevant industries	Yearly	Period 5: 50% Period 6: 30% Period 7: 30% Period 8: 40%
	Center's alumni pursuing research in disciplines related to the Center at academia & research labs *(added in Period 6)*	Yearly	Period 6: 30% Period 7: 30% Period 8: 30%
	Technology development attributable to Center's research • Low energy devices • Enabling other applications	Yearly	Period 6: 0 Period 7: 0 Period 8: 1
	• Number of external articles on the Center *(discontinued)*	Yearly beginning in Period 3	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase

1c. *Problems Encountered*

Nothing to report.

2a. *Knowledge Transfer Activities in Period 8*

Dissemination of results and outcomes from research, education and diversity activities remain the key knowledge transfer avenue of the Center for E^{3}S. As in previous years, 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.

In period 8, so far, the Center for E^3S has published 25 papers in journals, and four are under review. In addition, Prof. del Alamo (MIT) published a textbook: "Integrated Microelectronics Devices: Physics and Modeling," Pearson, 2017. Moreover, the papers from 22 talks, presented at peer-reviewed conferences, have been published as conference proceedings. Center members also presented an additional 59 talks and 24 posters at other scientific conferences and meetings.

On October 19 and 20, the Center for E3S organized again the Berkeley Symposium for Energy Efficient Electronic Systems. This year marked the fifth installment of this biennial event, which has become one of the leading events in low-energy electronics. New this year was that the Berkeley Symposium joined forces with the Steep Transistors Workshop with the goal of further expanding its reach and impact. The joint event presented a unique forum for speakers, from academia, industry, and government laboratories, to share their perspectives, discuss issues, and present new approaches. The joint event was co-sponsored by IEEE, and included keynote presentations, invited and contributed talks, as well as a poster session (see Appendix G for detailed program). The Symposium brought together a wide array of researchers from around the world working on breakthrough improvements in energy efficiency for information processing – from devices to systems. This international event attracted presenters from twelve countries and of the 134 registered attendees, 77 were unaffiliated with the Center for E3S. Out of the 77 unaffiliated attendees, 21 were from industry and four were from National Labs. This year's event featured 27 oral presentations (including talks by representatives from Hitachi, Intel, GlobalFoundries, IMEC, CEA Leti and IRDS) and 33 poster presentations. The Center contributed 6 talks and 16 posters. We also invited five student and one faculty representatives from our summer education programs (REU, TTE-REU, RET, iETERN) to attend the symposium and present a poster about their work at E3S. The students and the faculty member greatly enjoyed the meeting and emphasized that meeting with these international researchers and presenting a poster was a wonderful experience.

In addition to strong interactions with industry surrounding the Berkeley Symposium, the Center has continued seeking input from its 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.

Another important knowledge transfer vehicle is the Center for E3S website. In this period, we have completely re-designed our website and updated all content. The new website is based on Wordpress and will be easy to maintain for Center staff. The link to the new website is: https://e3s-center.berkeley.edu/. The new website was designed to be a major recruiting tool with a Twitter and Facebook portal, as well as a blog site. The Center for E^3S 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 Center activities and programs, key outcomes, and general stories related to energy efficient electronics.

The Center has also continued to transfer knowledge gained from the Center's research and education activities in the areas of low-energy electronics to other applications. Technologies that are pursued by E^3S faculty with external partners include "Squitch Switches as Analog Valves", "RIE Process with Digital Etch Technology for III-V Features of High Aspect Ratios", and "Negative Capacitance Transistors".

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

- *Dissemination of Results*

  The main knowledge transfer venue has continued to be dissemination of research and education results by E^{3}S researchers through publications in peer-reviewed journals and at scientific conferences. In addition, the Center has continued to provide avenues for its REU interns to go to scientific conferences and present their research activities through talks and posters, including poster presentations at this year's Berkeley Symposium for Energy Efficient Electronic Systems.

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.	FIU	Miami, FL

So far in this reporting period, the Center's faculty, postdocs, students, staff, and collaborators have published 29 papers (including four submitted manuscripts), all in peer-reviewed journals. 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 citations for the 184 papers attributed to the Center was 4361, an increase of 60 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 8, 26 talks by researchers from all E3S member institutions were published in conference proceedings, including IEEE International Electron Devices Meeting, CLEO, IEEE Photonics Society Conference, and IEEE Bipolar/BiCMOS Circuits and Technology Meeting.

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.	UTEP	El Paso, TX
3.	NOBCCHe National Organization of Black Chemist & Chemical Engineers Conference	Minneapolis, MN
4.	SACNAS Annual Conference	Salt Lake City, UT

5.	Fifth Berkeley Symposium on Energy Efficient Electronic Systems	Berkeley, CA

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 8, four students presented their work at the SACNAS Conference in October, one student presented her work at the NOBCCHe National Organization of Black Chemist & Chemical Engineers Conference, and another student presented at the Fifth Berkeley Symposium on Energy Efficient Electronic Systems.

Table 4.5. Granted Patents & Patent Applications

Led by	**E³S Researchers**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	FIU	Miami, FL
3.	MIT	Cambridge, MA

So far, in period 8, E^{3}S researchers at UC Berkeley, MIT, and FIU applied for five patents (one from Theme I, one from Theme II, and three from Theme IV). One of the patent applications has been granted U.S. Provisional Application status.

Table 4.6. Fifth Berkeley Symposium on Energy Efficient Electronic Systems

Led by	**Eli Yablonovitch, Jeffery Bokor, Michael Bartl**	
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
6.	The full list of attendees and their organizations is given in Appendix G	

The 5th Berkeley Symposium on Energy Efficient Electronic Systems offered technical sessions that range from devices to systems to provide researchers an integrated perspective of the challenges and advances in energy efficiency for information processing systems (see Appendix G for symposium program). IEEE Electron Devices Society was a technical co-sponsor of the Symposium. The Organizing Committee was co-chaired by Profs. **Eli Yablonovitch** and **Jeffery Bokor** (both *Berkeley*). Dr. **Michael Bartl** (*Berkeley*) took the role of executive chair of the symposium. This international event attracted presenters from twelve countries and of the 134 registered attendees, 77 were unaffiliated with the Center for E3S. Out of the 77 unaffiliated attendees, 21 were from industry and four were from National Labs. This year's event featured 27 oral presentations (including talks by representatives from Hitachi, Intel, GlobalFoundries, IMEC, CEA Leti and IRDS) and 33 poster presentations.

Table 4.7. HBCU E3S Workshop

Led by	**Kedrick Perry**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Hampton University	Hampton, VA
3.	Prairie View A&M University	Prairie View, TX
4.	Norfolk State University	Norfolk, VA
5.	Virginia State University	Petersburg, VA
6.	University of Maryland Eastern Shore	Princess Anne, MD

Following the inaugural HBCU E3S Workshop in spring 2016, the center organized the second edition of this successful workshop in spring 2017. The aim of the workshop was to bring to Berkeley faculty from HBCU schools from which students were accepted into the 2017 HBCU summer REU program (Tsu-Jae King Liu, PI). This REU program is funded by the University of California Office of the President and is managed and operated by E^3S staff as part of our summer REU portfolio. During the two-day workshop, HBCU faculty members interacted with E3S host faculty, staff, and students/mentors, enjoyed a tour of UC Berkeley labs including the cleanroom, and social activities on and off campus. Furthermore, the workshop agenda (see Appendix H) featured presentations by HBCU and UC Berkeley faculty as well as information sessions about the REU program and the UC Berkeley EECS graduate program.

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

As a Science and Technology Center, the Center for E3S continues to seek possibilities of transferring some of the 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. They have proven to be transformational. Excellent devices results have demonstrated the potential of III-V MOSFETs for future CMOS. During period 8, Prof. **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

Prof. **Sakhrat Khizroev** (*FIU*) received an industry award from Turning Point Brands to spin out some aspects of his magnetic nanoparticle work developed in the Center's nanomagnetics research theme. The focus of this project is to comparatively study primary and secondary battery cells based on magnetoelectric nanoparticles.

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 E3S. However, since the anticipated overall device characteristics did not fit the main goals of the Center, this research was moved out of E3S, and the new Berkeley Center for Negative Capacitance Transistors was formed with broad industry support from Intel, TSMC and GlobalFoundries, and Profs. **Sayeef Salahuddin** and **Chenming Hu** (both *Berkeley*) as co-directors.

- *Knowledge Transfer into the Center*

  As mentioned above, the Center for E^3S is a strong advocate for knowledge transfer as a two-way interaction. The Center thus continues 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.	IBM	Yorktown Heights, NY
8.	Intel Corp.	Hillsboro, OR
9.	Lam Research	Fremont, CA

This year, the five companies comprising the E^{3}S Industrial Research Board were invited to both the Center's Annual Retreat and the Fifth Berkeley Symposium on Energy Efficient Electronic Systems. Four of the five members send representatives (see table above) were able to attend at least one of the two events. During these events the Center leadership team, faculty, students, postdocs and staff had ample time to interact with industry members, update them on current projects and plans, and receive valuable feedback.

Table 4.13. Seminars by Invited Speaker

Led by	**Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	Institute of Bioengineering and Nanotechnology	Singapore
2	TSMC	Taiwan
3.	Lam Research	Fremont, CA
4.	UC Berkeley	Berkeley, CA
5.	MIT	Cambridge, MA
6.	Stanford	Palo Alto, CA
7.	UTEP	El Paso, TX
8.	FIU	Miami, FL

In this period, the Center management organized two seminars by external speakers: Dr. **Nerissa Draeger** (*Lam Research*) and Dr. **Jack Sun** (*TSMC*). In addition, the Center co-organized a seminar by Dr. Jackie Ying (*Singapore Institute of Bioengineering and Nanotechnology*). More details about seminars can be found at *https://e3s-center.berkeley.edu/news-events/seminars/*. It should be emphasized that these seminars also attracted attendees from outside the Center, participating either in person or *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, the E^{3}S graduate students and the summer REU student cohort visited again the headquarters of our industry partner Lam Research. This visit was coordinated by our education manager (**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's education and diversity programs have continued their strong interactions with the broader community and engaged in knowledge transfer through written and oral dissemination of best practices, curriculum development and dissemination, and in-person outreach. The Center was present at eleven education, diversity and recruiting events, including the National Society of Black Engineers (NSBE) Conference, the American Indian Science & Engineering Society (AISES) Conference, the National Organization of Black Chemist & Chemical Engineers (NOBCChE) Conference, 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. In addition, the education and diversity directors visited 13 universities and colleges, and gave presentations to students and faculty.

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 2016	New Orleans, LA

E^3S education associate director, **Lea Marlor**, presented a paper at the peer-reviewed American Society for Engineering Education Conference (ASEE) in June 2017 on "A Follow Up Study on the Impact of Summer Research Experiences on Community College Students Career Paths". 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*

Objective	Metric	Targets	Results						
			P 2	P 3	P 4	P 5	P 6	P 7	P 8
Knowledge Transfer	Center publications	P2: 18 P3: 18 P4: 18 P5: 18 P6: 25 P7: 25 P8-P10: 30	17	17	19	39	45	41	39 (7 subm.)

	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26
	Center sponsored symposia & workshops	P2: Baseline P3: 0 P4: 1 P5: 0 P6: 2 P7: 1 P8-P9: 1 P10: 2	1	0	1	0	1	1	2
	External citations of publications *(cum)*	P3: 10 P4: 100 P5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase
	Contacts with industry:								
	• Talks & Meetings	All Periods: 36	66	20	42	62	35	42	31
	• Industry Presentations	All Periods: Yearly: 2	4	2	6	3	5	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8
	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

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

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 9*

The Center will continue its active and diverse knowledge transfer program in period 9 and look for opportunities to further extend and strengthen activities.

An area the Center plans to become stronger involved is knowledge transfer from our successful educational and diversity programs, in particular, our summer research experience programs for California community college students and faculty. Together with our external evaluator, **Catherine Amelink**, Center education and diversity directors **Lea Marlor** and **Kedrick Perry**, respectively, plan to make details about the programs (from recruitment to program activities and longer-term outcomes) available to the community and the general public through publications and conference presentations.

As announced in last year's report, in this period we also launched a Center for E^{3}S site on the *nanoHUB.org* website platform. While content development for this new site is currently still under construction, it will be used mainly for educational purposes and will include publication of an open-access e-book on energy efficient electronics. The e-book project is underway and several chapters should be ready for release in period 9.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

As an NSF Science and Technology Center, E^3S embraces the opportunity to develop new collaborations and nurture existing ones within the Center and with external partners. In this regard, the multi-institutional structure of E^3S is ideally suited to extend its collaborative nature to external partners. The Center considers external entities as important partners to its success at all Center aspects: research, education, knowledge transfer and broadening participation. The Center's researchers have thus established both formal and informal partnerships with researchers in academia, industry, and research labs as they pursue their scientific investigations. 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^3S. 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 8, 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	Period 6: 3 Period 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^3S regards industry partnerships as critical to the success of practical implementation of its research outcomes. However, this—in no way—implies that E^3S 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 8

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

- Participation as a member in the E^3S 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 7, three of the five member companies had additional engagement with the Center beyond an advisory level.

- Applied Materials has a partnership with **Jing Kong** (*MIT*) for characterizing and evaluating the 2D materials synthesized by the Applied Materials R&D team.
- Lam Research has a continued partnership with **Jesus del Alamo** (*MIT*) to conduct laboratory evaluation of the high aspect ratio digital etch technology for broader semiconductor applications.
- Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) is an elected Board of Directors member at Intel Corporation.

- Other companies work with the Center in focused and limited manner.
  - ARM provided access to internal tools and models to the **Wong** group (*Stanford*) for developing a modeling framework to analyze the energy efficiency of processor cores.
  - TSMC is setting up a research collaboration with **Philip Wong** to identify the benefits of various 2.5D and 3D integration technologies for achieving high energy efficiency of computing systems.
  - ASML collaborates with **Philip Wong** on studying the system-level benefits of various emerging memory technologies (e.g. RRAM, STT-MRAM) for achieving high energy efficiency of computing systems.
  - Turning Point Brands has awarded **Sakhrat Khizroev** (*FIU*) a monetary industry award to comparatively study primary and secondary battery cells based on magnetoelectric nanoparticles
  - Lockhead Martin is in the process of setting up a research collaboration with the **Khizroev** group for research on sub-10μm STT-MTJ spintronics.
  - FLIR has started a collaboration with **Junqiao Wu** (*Berkeley*) to study properties of their films, related to energy-efficient infrared switches.

CEA Leti, a French government laboratory in Grenoble, France has become an important education and research partner of the Center for E^{3}S. The Center's engagement with CEA-Leti started in 2014 with an education partnership. This education partnership has continued with **Louis Hutin** (*CEA-Leti*) hosting **Elizabeth Avelar Mercado** and **Alam Figueroa Aguilar**, both undergraduate researchers with the Center, for 9 weeks for doing research in CMOS 3D sequential integration flow simulation and developing software to correlate data, respectively.

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.

This summer we partnered with the Louis Stoke Alliance for Minority Participation (LSAMP) program at UTEP to host E^{3}S REU student Nicohl Cintron Rodriquez. LSAMP seeks to increase the number of underrepresented minority students pursuing degrees in science, technology, engineering, and mathematics (STEM careers). The University of Texas System LSAMP program is funded by NSF.

In period 8, the Center provided a mentoring experience to one student of the Center for Integrated Access Networks (CIAN) REU program at Berkeley. CIAN is a research center based at the University of Arizona, with faculty at Berkeley that are also E^{3}S faculty. As the research areas are similar, we provided the student with a cohort of fellow interns so that they had a more positive experience researching 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

Metric	Targets	Results						
		P 2	P 3	P 4	P 5	P 6	P 7	P 8
Contacts with industry:								
• Talks & Meetings	All Periods: 36	66	20	42	62	35	42	31
• Industry Presentations	All Periods: Yearly: 2	4	2	6	3	5	2	2
Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8

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 9

Center director **Eli Yablonovitch** will continue to present the photoreceiver systems level solution developed in the nanophotonics theme to representatives of the silicon photonics industry, who appeared to be poised to adopt these innovations. If this serendipitous technology spinout occurs, it will be one of the important legacy successes of the Center for E^{3}S.

Recent developments in nanomechanics theme research on NEM switches based integrated circuits (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 9, while new ones will be formed as opportunities arise.

During summer 2018, 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 8, 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, the recently funded NIH Center for Genomics Editing and Recording (PI: Jennifer Doudna) has agreed to expand the TTE program by funding four additional students. Additionally, the Center is in discussions with the Tsinghua-Berkeley Shenzhen Institute, which is co-cirected by E^{3}S Faculty member, **Prof. Chang-Hasnain**, about possible expansion with this group on Berkeley's campus.

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 college attendees who may identify as underrepresented based on their racial/ethnic group, gender, LBGTQ status, veteran status, first-generation status, socioeconomic status, and ability/disability status.

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 it 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 8, 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 first-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 students from five HBCUs: Prairie View A&M University, Norfolk State University, Virginia State University, University of Maryland Eastern Shore, and Hampton University. 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. We were fortunate to have faculty representation from each HBCU listed above. The Center plans on writing a proposal to UCOP in early 2018 for continued funding of the HBCU initiative.

In period 8, 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 of Women Engineers (SWE), the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS), the CUR Symposium, and the EEC Grantees Conference; and **Kedrick Perry** attended the conferences for the American Indian Science and Engineering Society (AISES), Society of Hispanic Professional Engineers (SHPE), National Organization of Black Chemists & Chemical Engineers (NOBCChE), 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^3S 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^3S. During the annual retreat of Period 8, **Kedrick Perry** once again gave a talk incorporating concepts of diversity including: ableism, privilege, perception, assimilation, othering, and identity.

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% Period 6: 25% Period 7: 25% Period 8: 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%
	Participants from underrepresented* groups in the Center's Diversity programs	Annually	Period 3: Baseline Period 4: 80% Period 5: 85% Period 6: 85% Period 7: 85% Period 8: 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%
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate *(new)*	Annually beginning in Period 6	Period 6: 85% Period 7: 85% Period 8: 85%
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering *(new)*	Annually beginning in Period 6	Period 6: 80% Period 7: 80% Period 8: 80%

1c. Problems Encountered

In period 8, the Center is still challenged by the lower than targeted 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^3S internship). While many former undergraduate students continue on to graduate school, they are not continuing their tenure on an E^3S 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 8, 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 8, 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: 43 Females: 20 (47%), URMs: 39 (91%)

As a founding member of the MIT Online Science, Technology, and Engineering Community (MOSTEC), the role of the Center for E^3S 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, 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: 3 (50%), First Gen: 5 (83%)

During summer 2017 (Period 8), E^{3}S at UC Berkeley hosted six of fifteen community college students in the TTE REU program (TTE REU Recruitment Flyer: https://e3s-center.berkeley.edu/download/3632/). These students completed nine weeks of research in the laboratories of E^{3}S faculty, **Tsu-Jae Liu, Sayeef Salahuddin** and **Jeff Bokor**; and E^{3}S Education Affiliate **Alex Zettl**. Education Affiliates are not part of the Center's research team, but their research disciplines are similar to those of the Center. **Alex Zettl** joined the Center as an affiliate in Period 5.

In Period 8, 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/2017/10/Draft-Calendar-for-website.pdf

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, 93% (28) 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, 89% (25) enrolled at a UC campus; 75% (21) enrolled at UC Berkeley, and 86% (24) 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), **Lea Marlor** (Berkeley), and **Eli Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx. Number of Attendees (if appl.)	Total: 13 Female: 5 (38%), URMs: 5 (38%)

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, students were hosted by **Timothy Swager** and **Jesus del Alamo**. At UTEP, the student was placed with **David Zubia**. At Berkeley, students were hosted by E^{3}S faculty, **Tsu-Jae King Liu**, **Jeff Bokor**, **Eli Yablonovitch**, **Vladimir Stojanovic, Constance Chang-Hasnain, Felix Fischer**, **Junqiao Wu**, **Laura Valler** (**affiliate**) 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/2017/05/2016_E3S_REU-Program_Calendar.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.

In an attempt to increase diversity in the E^{3}S REU program, this was the third year that a blind application review was used in the selection process. A blind review consists of taking out the name and any demographic information of an applicant (gender, race, veteran status, etc.). Blind reviews are a best practice approach to achieve more gender and racial parity.

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 8, 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.

Kedrick Perry visited four 4-year universities: University of Maryland-Baltimore County, Morgan State University, Clark Atlanta and Howard University. During these visits, the Center conducted graduate school workshops, information sessions, and/or faculty meetings. These activities were typically one-hour presentations on the Center's research themes and diversity programs and on how to prepare for graduate school. At the diversity conferences, the Center helped sponsor a booth at the graduate fairs for prospective undergraduate and graduate students to meet Center members. These booths also offered the chance to learn about the Center's research areas and opportunities for undergraduates, as well as graduate students and postdocs.

For the community college programs, **Lea Marlor** visited nine 2-year colleges: Allan Hancock, Santa Barbara City College, Ventura College, San Diego City College, Southwestern College, El Camino College, Santa Ana College, and LA Trade Technical College, Diablo Valley College; with plans to visit Sacramento City College in January. Additionally, five 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 8, 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 8. 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*

Objective	Metric	Targets	Results P 2	P 3	P 4	P 5	P 6	P 7	P 8
Diversity	Women in the Center's research programs	P2: Baseline	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)	12 (14%)
		P3: 5% increase							
		P4: 30%							
		P5: 20%							
		P6: 25%							
		P7: 25%							
		P8-P10: 25%							
	Underrepresented minorities in the Center's research programs	P2: baseline	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)	11 (13%)
		P3: 15% increase							
		P4: 5%							
		P5: 10%							
		P6: 10%							
		P7: 12%							
		P8: 12%							
		P9-10: 15%							
	Participants from underrepresented* groups in the Center's Diversity programs	P3: Baseline	n/a	93 (82%)	Women	Women	Women	Women	Women
		P4: 80%			37 (44%)	26 (41%)	29 (40%)	25 (40%)	38 (44%)
		P5: 85%			URM:	URMs	URMs	URMs	URMS
		P6: 85%			58 (68%)	36 (56%)	49 (67%)	38 (60%)	48 (55%)
		P7: 85%			Total:	Total	Total	Total	Total
					73 (86%)	49 (77%)	66 (90%)	63 (87%)	69 (80%)
		P8-P10: 85%							
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in	P 6: 40%	(new for P6-10)				17 (55%)	23 (54%)	27 (50%)
		P7: 45%							
		P8-P10: 50%							

	disciplines related to the Center					
	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%)
	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%)

***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 9

In period 9, the Center will continue to be staffed by Associate Director for Education, **Lea Marlor**, and Diversity Director, **Kedrick Perry**. E^3S 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 of which Theme Leader **Tsu-Jae Liu** is the PI. **Liu** and **Perry** hosted an HBCU workshop for faculty in the Spring of 2017 with plans to host another one in the Spring of 2018. **Perry** will also continue to seek out funding to continue the diversity and education programs.

In period 8, 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 9 along with the use of national databases to target prime candidates, enhancing the profile of E^3S 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^3S is given in Appendix B. The most notable changes are (1) the promotion of **Lea Marlor** to associate director of education, and (2) the addition of **Kedrick Perry** (director of diversity and outreach) and **Lea Marlor** (associate director of education) to the Center's executive committee as regular voting members. Previously, both of them were observers (non-voting members). 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^3S 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)

b) The new executive board (including the addition of **Lea Marlor** and **Kedrick Perry**) was ratified at the July 31, 2017, Executive Committee meeting with 100% of the votes in favor.

c) The by-laws of the E^3S Executive Committee were reviewed by the Center's leadership team. No changes were recommended and the by-laws were ratified at the July 31, 2017, executive committee meeting with 100% of the votes in favor.

- E^3S Management and Operations Team:
  - E^3S 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: Period 2: 3 or higher Period 3: 3 or higher Period 4: 3 or higher Period 5: 3 or higher Period 6: 4 or higher Period 7: 4 or higher Period 8: 4 or higher
	• Co-PIs	Annually beginning in Period 3	
	• External Advisory Board	Annually	
	Authorship disputes	Annually beginning in Period 3	Period 2: 20% decrease Period 3: 20% decrease Period 4: 20% decrease Period 5: 20% decrease Period 6: 0 Period 7: 0 Period 8: 0
	Plagiarism	Annually	Period 2: 0 Period 3: 0 Period 4: 0 Period 5: 0 Period 6: 0 Period 7: 0 Period 8: 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 E3S leadership team.

Table 7.2. Center Management Metrics Table

Objective	Metric	Targets	Results P 2	P 3	P 4	P 5	P 6	P 7	P 8
Center Management	Annual Surveys:	According to Likert Scale:							
	• Students /Postdocs	P2: 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
	• Co-PIs	P3: 3 or higher P4: 3 or higher P5: 3 or higher P6-10: 4 or higher	No survey in Period 2	Leader-ship: 4.46 Collaboration 3.25	Leader-ship: 4.7±0.5 Collaboration n/a	Leader-ship: 4.9±0.1 Collaboration Outside Theme: 1.3+/-0.1 Within Theme: 3+/-1	Leader-ship 4.6±0.1	Leader-ship 4.8±0.2	Leader-ship 4.8±0.1
	• External Advisory Board		Strategic Plan: 4.18 Center Status: 4.01	Strategic Plan: 4.07 Center Status: 3.96	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
	Authorship disputes	P2: 20% decrease P3: 20% decrease P4: 20% decrease P5: 20% decrease P6-10: 0	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale	0	0	0	0
	Plagiarism	All Periods: 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

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 K) and 2) faculty survey (see also Appendix L). Period 8 has been the seventh 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 4.4 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 also in response to last year's survey response, the 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 3.7 with a standard deviation of 1.3. Two things are interesting to note: 1) While this score is lower than all others, this is still a positive score on the Likert scale. 2) The large standard deviation (by far the largest for all questions) indicates that students are strongly divided on this question. The Center management and leadership takes this result very serious and regards it as a call to better inform all students and postdocs about the multi-institutional research and education opportunities in the Center, including the E^3S Graduate Student and Postdoc Rotation program. This program enables students and postdocs to spent several months at an E^3S partner institution to perform research or use facilities not available at their own institution.

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

	P2	P3	P4	P5	P6	P7	**P8**
Inclusiveness	3.8	4.1	4.1	4.6	4.4	4.3	**4.5**
Teamwork	3.7	3.6	4.0	4.6	4.2	4.2	**4.3**
Open and timely communications	4.0	4.2	4.2	4.7	4.2	4.4	**4.5**
Agility/Decision Making	4.0	4.1	4.2	4.5	4.4	4.4	**4.4**
Focus on Performance	3.8	4.1	4.1	4.5	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^3S colleagues act in an ethical manner*" with YES.

1d. Problems Encountered

The planned annual meeting of the Center's Education Working Group (with selected members of the E^{3}S External Advisory Board) had to be postponed to spring since we were unable to find a date that would have worked for the majority of the members of this body. However, many of the External Advisory Board members attended the 5th Berkeley Symposium on Energy Efficient Electronics Systems (see also section Knowledge Transfer). Therefore, the Center leadership team, and in particular the directors of education and diversity, had ample time to interact with those members to discuss current education, diversity and outreach efforts, and obtain valuable feedback.

2. Management and Communications Systems

Management: The E^{3}S Executive Committee regularly meets six times throughout the funding period to discuss the direction of the Center and make important decisions. Due to the multi-institutional nature of the Executive Committee with members from UC Berkeley, MIT, Stanford and UTEP, these meetings are held through remote participation via Webex. So far, the Executive Committee has met five times in period 8 with the sixth and final meeting being scheduled for December 14 (see details below).

The executive committee conducted its annual review of all proposed research programs for funding period 9 in October and final discussions were made at the November 20 executive committee meeting. Guidance for both the Center investigators (proposers) and the executive committee members (reviewers) were both the Centers strategic plan as well as longer-term Center legacy considerations. 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 8

Meeting Dates	Agenda Topics
March 2, 2017	Site Visit Recommendations; Budget Discussion; External Advisory Board Membership Review
April 24, 2017	Review of Period 8 Budget; Annual Retreat Planning; Berkeley Symposium Planning; Update on Website Re-Design
July 31, 2017	Review and Ratification of By-Laws; Approval of Executive Board; Approval of External Advisory Board Membership; External Advisory Board Meeting Planning; Berkeley Symposium Planning
September 8, 2017	Annual Retreat Debrief; Proposal Review Planning; Berkeley Symposium Planning; Site Visit Agenda Discussion
November 20, 2017	Center-wide Annual Proposal Review; Berkeley Symposium Debrief
December 18, 2017	Review of the Center's Results vs. the Strategic Plan; Review of Preliminary Feedback from External Advisory Board; Site Visit Planning

Communications and Planning: This year, the center-wide annual retreat—the foremost gathering and planning event for all Center faculty, students, postdocs and staff—was held on September 7 and 8 at MIT. 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. The theme for this year's retreat was *Planning Our Legacy*. 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 I) for which we also welcomed

Dr. Paul Solomon from our industry partner IBM. Furthermore, the retreat provided opportunities for presentations about education and diversity achievements and plans, reports by the executive director on Center management and center-wide output, and a diversity refresher training/workshop on *Inclusivity* by diversity director, **Kedrick Perry**. At this year's event, we also had a guest speaker, **Prof. Dirk Englund** from MIT, who gave a presentation on *Large-Scale Photonic Integrated Circuits for Quantum Information Science and Machine Learning*.

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.

Another important Center-wide communications tool is the E3S website. We are excited to report that the Center website was completely re-designed and updated in period 8. The link to the new website is: https://e3s-center.berkeley.edu/. The new website was designed to be a major recruiting tool with a Twitter and Facebook portal, as well as a blog site and will be used to keep 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: one 2-year term
- Members: one 3-year term to be followed by, at the discretion of the E^{3}S Executive Committee, additional 2-year appointments.

Limited-term membership was implemented at the beginning of the Center both to lessen the concern that an engagement as an E^{3}S 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.

The E3S External Advisory Board is chaired by **Paolo Gargini** (*IRDS*) and current members are:

Table 7.4. Center for E3S 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
Katherine Guzman	Sandia National Lab
Jonathan Heritage	University of California, Davis
Diane Rover	Iowa State University
Thomas Theis	Columbia University

Center for Energy Efficient Electronics Science

Changes from last funding period: 1) **Daniel Radack** (*Institute for Defense Analysis, IDA*) completed his five-year term with the ending of period 7. He was thanked for his excellent service to the Center and were excused from the External Advisory Board. 2) **Thomas Theis** (*Columbia University*), who just moved after a distinguished career at IBM to Columbia University as executive director of the Columbia Nano Initiative, joined the External Advisory Board in March of this year.

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. As mentioned above, due to scheduling issues, the next meeting of this advisory body has been moved to spring of 2018.

The annual meeting of the E^{3}S External Advisory Board took place on October 18 (the agenda is given in Appendix B). The main purpose of these annual meeting 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.

Seven of the eight current members of the External Advisory Board participated in this year's meeting. **Diane Rover** (Iowa State University) was unable to attend due to a scheduling conflict with an NSF Review Board commitment. The full list of attendees was:

- Samuel Bader, Argonne National Lab
- Eun-Woo Chang, Ashland University
- Paolo Gargini, IRDS (*Chair*)
- Elsa Garmire, Dartmouth College
- Katherine Guzman, Sandia National Lab
- Jonathan Heritage, University of California, Davis
- Thomas Theis, Columbia University

Following the presentations by E^{3}S 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, the student and postdoc speakers and poster presenters, and the new education and diversity initiatives. The External Advisory Board emphasized the importance to make longer-term goals (beyond the duration of the Center) and to seek 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.

Since the External Advisory Board meeting (October 18, 2017) was held the day before the start of the 5th Berkeley Symposium on Energy Efficient Electronic Systems, October 19-20, 2017 (see also Knowledge Transfer, section 2a), all board members were invited to stay for the symposium. Several board members accepted our invitation and attended the oral and poster presentations (with many E3S students and postdocs presenting). In addition, this also provided additional opportunities for the E3S leadership team to interact with the External Advisory Board.

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	David Hemker
IBM	Ghavam Shahidi

Hewlett-Packard	Stan 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 E3S investigators, (2) participation of board members at the E3S Annual Retreat and the Berkeley Symposium on Energy Efficient Electronic Systems, (3) presentations by board members to our students, postdocs and faculty, and (4) hosting of E3S students and postdocs.

The industry partners in attendance at the Annual Retreat and/or the Berkeley Symposium were:

- Namsung Kim, Applied Materials
- John Ducovic, Applied Materials
- Nerissa Draeger, Lam Research
- Paul Solomon, IBM
- Uygar Avci, Intel

Unfortunately, **Stan Williams** from HP Enterprise was unable to attend the Annual Retreat or the Berkeley Symposium due to scheduling conflicts.

All industry partners in attendance participated actively in discussions and analyses of research results. Industrial Research Board members provided detailed feedback and comments to the E3S leadership team. In addition, **Nerissa Draeger** (*Lam Research*) acted as chair of the *New Mechanisms for Energy Efficient Computing* session at the Berkeley Symposium.

4. Changes in the Strategic Plan

No changes have been made to the Center for E^3S 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

<u>Journal Articles Published</u> *(Chronological)*

1. D. Chen, Z. Chen, Q. He, J. Clarkson, C. Serrao, A. Yadav, M. Nowakowski, Z. Fan, L. You, X. Gao, D. Zeng, L. Chen, A. Borisevich, **S. Salahuddin**, J.-M. Liu, and **J. Bokor**, "Interface Engineering of Domain Structures in $BiFeO_3$ Thin Films," *Nano Letters*, vol. 17, no. 1, pp. 486-493, Dec 2016.
2. G.N. Malheiros-Silveira, I. Bhattacharya, S.V. Deshpande, D. Skuridina, F. Lu, **C. Chang-Hasnain**, "Room-temperature Fabry-Perot Resonances in Suspended InGaAs/InP Quantum-well Nanopillars on a Silicon Substrate", *Optics Express, vol.* 25, no. 1, pp. 271-277, Jan 2017.
3. S. Deshpande, I. Bhattacharya, G. Malheiros-Silveira, K. Ng, F. Schuster, W. Mantei, K. Cook, and **C. Chang-Hasnain**, "Ultracompact Position-Controlled InP Nanopillar LEDs on Silicon with Bright Electroluminescence at Telecommunication Wavelengths," *ACS Photonics*, vol. 4, no. 3, pp. 695-702, Feb 2017.
4. F. Schuster, J. Kapraun, G. Malheiros-Silveira, S. Deshpande, and **C. Chang-Hasnain**, "Site-controlled Growth of Monolithic InGaAs/InP Quantum Well Nanopillar Lasers on Silicon," *Nano Letters*, vol. 1, no.4, pp. 2697-2702, Mar 2017.
5. B. Saha, A. Peschot, B. Osoba, C. Ko, L. Rubin, **T.-J. K. Liu** and **J. Wu**, "Reducing adhesion energy of micro-relay electrodes by ion beam synthesized oxide nanolayers," *APL Materials*, vol. 5, no. 3, p. 036103, Mar 2017.
6. B. Senkovskiy, A. Fedorov, D. Haberer, M. Farjam, K. Simonov, A. Preobrajenski, N. Marternsson, N. Atodiresei, V. Caciuc, S. Blugel, A. Rosch, N. Verbitskiy, M. Hell, D. Evutushinsky, R. German, T. Marangoni, P. van Loosdrecht, **F. Fischer**, and A. Gruneis, "Semiconductor-to-Metal Transition and Quasiparticle Renormalization in Doped Graphene Nanoribbons," *Adv. Electron. Mater*, vol. 3, no. 4, pp. 1600490, Mar 2017.
7. T. Theis and **H.-S. P. Wong**, "The End of Moore's Law: A New Beginning for Information Technology," *IEEE Computing in Science & Engineering*, vol. 19, no. 2, pp. 41-50, Mar-Apr 2017.
8. G. Malheiros-Silveira, F. Lu, I. Bhattacharya, T.-T. Tran, H. Sun, and **C. Chang-Hasnain**, "III–V Compound Semiconductor Nanopillars Monolithically Integrated to Silicon Photonics,"*ACS Photonics*, vol. 4, no. 5, pp. 1021-1025, Apr 2017.
9. E. Stimphil, A. Nagasetti, R. Guduru, T. Stewart, A. Rodzinski, P. Liang, and **S. Khizroev**, " Physics considerations in targeted anticancer drug delivery by magnetoelectric nanoparticles," *Appl. Phys. Rev*., vol. 4, no. 2, pp. 021101, Apr 2017.
10. D. J. Connelly and **T.-J. K. Liu**, "Modeling nanoelectromechanical switches with random surface roughness," *IEEE Trans. Electron Dev.*, vol. 64, no. 5, pp. 2409-2416, Apr 2017.
11. 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.
12. X. Zhao, C. Heidelberger, **E. Fitzgerald**, and **J. A. del Alamo**, "Source/Drain Asymmetry in InGaAs Vertical Nanowire MOSFETs," IEEE Trans. Electron Dev., vol. 64, no. 5, pp. 2161-2165, May 2017.
13. 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.

14. A. Nagesetti, A. Rodzinski, E. Stimphil, T. Stewart, C. Khanal, P. Wang, R. Guduru, P. Liang, I. Agoulnik, J. Horstmyer, and **S. Khizroev**, "Multiferroic coreshell magnetoelectric nanoparticles as NMR sensitive nanoprobes for cancer cell detection," *Scientific Reports*, vol. 7, no. 1610, May 2017.
15. 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.
16. F. Lu, I. Bhattacharya, H. Sun, T.-T. Tran, K. Ng, G. Malheiros-Silveira, and **C. Chang-Hasnain**, "Nanopillar Quantum well lasers directly grown on silicon w and emitting at silicon-transparent wavelengths, *Optica*, vol. 4, no.7, pp. 717-723, Jun 2017.
17. 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.
18. 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.
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20. J. Lin, X. Cai, **D. Antoniadis**, and **J. A. del Alamo**, "The Importance of Ballistic Resistance in the Modeling of Nanoscale InGaAs MOSFETs," *IEEE Electron Device Lett.*, vol. 38, no. 7, pp. 851-854, Jul 2017.
21. 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.
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. J. P. Llinas, A. Fairbrother, G. Borin Barin, W. Shi, K. Lee, S. Wu, B. Yong Choi, R. Braganza, J. Lear, N. Kau, W. Choi, C. Chen, Z. Pedramrazi, T. Dumslaff, A. Narita, X. Feng, K. Mullen, **F. Fischer**, A. Zettl, P. Ruffieux, **E. Yablonovitch**, M. Crommie, R. Fasel, and **J. Bokor**, "Short-channel field-effect transistors with 9-atom and 13-atom wide graphene nanoribbons," *Nat. Commun*, vol. 8, pp. 633, Sept 2017.
24. 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.
25. A. Vardi, J. Lin, W. Lu, X. Zhao, A. Fernando-Saavedra and **J. A. del Alamo**, "A Si-Compatible Fabrication Process for Scaled Self-Aligned InGaAs FinFETs," *IEEE Trans. Semiconductor Manufacturing*, vol. 30, no. 4, pp. 468-474, Nov 2017.
26. 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)*, Dec 2017. (Accepted).
27. R. Durr, D. Haberer, Y.-L. Lee, R. Balckwell, A. Kalayjian, A. Marangoni, J. Ihm, **S.G. Louie**, and **F. Fischer**, "Orbitally Matched Edge-Doping in Graphene Nanoribbons," *J. Am. Chem. Soc.*, ASAP Article, DOI: 10.1021/jacs.7b11886, Dec 2017. (Accepted)

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

1. K. Dong, H. 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," submitted to *Small* (2017).
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," submitted to *IEEE Trans. Electron Dev*. (2017).
3. 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.-W. Choi, **F. Fischer**, **S. G. Louie**, and M. Crommie, "Concentration dependence of dopant electronic structure in bottom-up graphene nanoribbons," submitted to *Nature Communications* (2017).
4. J. Hong, M. Stone, B. Navarette, K. Luongo, Z. Yuan, K. Xia, N. Xu, **J. Bokor**, L. You, **S. Khizroev**, "3D multilevel spin transfer toque devices," submitted to *Appl. Phys. Lett.* (2017).

Conference Proceedings (Chronological)

1. F. Schuster, J. Kapraun, G. Malheiros-Silveira, S. Deshpande, and **C. Chang-Hasnain**, "Lasing of Site-Controlled InGaAs/InP Quantum Well Nanopillars Grown on Silicon," *CLEO*, May 2017.
2. X. Zhao, C. Heidelberger, **E. Fitzgerald** and **J. A. del Alamo**, "Top-Down InGaAs Vertical Nanowire MOSFETs with Record Characteristics," *CSW Compound Semiconductor Week*, May 2017.
3. A. Vardi, J. Lin, W. Lu, X. Zhao and **J. A. del Alamo**, "A Si-Compatible Fabrication Process for Scaled Self-Aligned InGaAs FinFETs," *CS MANTECH*, May 2017 (Invited).
4. **J.A. del Alamo**, "Nanometer-Scale III-V 3D MOSFETs?," *ALE*: *4th International Atomic Layer Etching Workshop*, Jul 2017 (Invited).
5. **J.A. del Alamo**, X. Cai, J. Lin, W. Lu, A. Vardi, and X. Zhao, "CMOS beyond Si: Nanometer-Scale III-V MOSFETs," *31st Annual IEEE Bipolar/BiCMOS Circuits and Technology Meeting*, Oct 2017 (Invited).
6. **J.A. del Alamo**, X. Zhao, W. Lu, and A. Vardi, "Towards Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs and TFETs," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017 (Invited).
7. S. Almeida, **D. Zubia**, A. Vidaña, and M. Martinez, "Conductance Modulation in 2D Materials by NEMS for Lower-Power Applications," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
8. S.A. Fortuna, C. Heidelberger, N. Andrade, **E.A. Fitzgerald**, **E. Yablonovitch**, and **M.C. Wu**, "Large Spontaneous Emission Rate Enhancement in a III-V Antenna-LED," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
9. 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.
10. J. Gorchon, C.-H. Lambert, Y. Yang, A. Pattabi, **S. Salahuddin** and **J. Bokor**, "Single shot ultrafast all optical magnetization switching of ferromagnetic Co/Pt multilayers," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.

11. P.-C. Shen and **J. Kong**, "Chemical Vapor Deposition of High-Quality Monolayer Transition Metal Disulfides," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
12. S. K. Vadlamani and **E. Yablonovitch**, "On the broadening of energy levels in a quantum dot-based tunnel transistor," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
13. T. Cao, F. Zhao, Y.-L. Lee and **S.G. Louie**, "Graphene Nanoribbons for Transistor Applications," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
14. J. A. Incorvia, E. Barre, S. H. Kim, C. McClellan, E. Pop, **H.-S. Wong** and T. Heinz, "Near-room temperature electrical control of spin and valley Hall effect in monolayer WSe2 transistors for spintronic applications," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
15. S. Hooten and **E. Yablonovitch**, "Metallodielectric Antenna for Spontaneous Emission Enhancement," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
16. A. El-Ghazaly, D. O'Mahoney, C.-H Lambert, J. Gorchon, P. –N. Brown, A. Pattabi, **H.S. Wong** and **J. Bokor**, " Ultrafast Magnetic Memory Bits Using All-Optical Magnetic Switching," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
17. N. Andrade, S. Fortuna, K. Han, S. Hooten, **E. Yablonovitch** and **M. Wu**, " Efficient and Broadband Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based nanoLED," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
18. B. Navarrete, M. Stone and **S. Khizroev**, "Properties of Magnetic Tunneling Junction Devices with Characteristic Sizes in Sub-5-nm Range," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
19. P. Zhao, M. Amani, D.-H. Lien, G. Ahn, D. Kiriya, J. Mastandrea, J. Ager, **E. Yablonovitch**, D. Chrzan and **A. Javey**, "Measuring the Edge Recombination Velocity of Monolayer Semiconductors," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
20. Z. Ye, H. Kam and **T.-J. King Liu**, "Negative Stiffness Structures for Energy Efficient MEM Switches," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
21. M. Amani, D.-H. Lien, D. Kiriya, G. Ahn, P. Zhao, J. Ager, **E. Yablonovitch** and **A. Javey**, "High Photoluminescence Quantum Yield in Transition Metal Dichalcogenides Enabled by Superacid Treatment," *Fifth Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop*, Oct 2017.
22. S. Fortuna, C. Heidelberger, N. Andrade, **E. Fitzgerald**, **E. Yablonovitch**, and **M. Wu**, "Controlling Surface Recombination in a Nanoscale III-V Light Emitting Diode," *IEEE Photonics Society Conference*, Oct 2017.
23. A. El-Ghazaly, C. H. Lambert, J. Gorchon, A. Pattabi, **H. S. P. Wong** and **J. Bokor**, "Ultrafast Magnetic Memory for Higher Data Rates and Smarter Cities," *The National Academics of Science, Engineering and Medicine - Arab American Frontiers Symposium*, Rabat, Morocco, Nov 2017.

24. X. Zhao, C. Heidelberger, **E. Fitzgerald**, W. Lu and **J. A. del Alamo**, “Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs,” *IEEE International Electron Devices Meeting*, Dec 2017.
25. A. Vardi, L. Kong, W. Lu, X. Cai, X. Zhao, J. Grajal and **J. A. del Alamo**, “Self-Aligned InGaAs FinFETs with 5-nm Fin-Width and 5-nm Gate-Contact Separation,” *IEEE International Electron Devices Meeting*, Dec 2017.
26. A. El-Ghazaly, C. H. Lambert, J. Gorchon, A. Pattabi, **H. S. P. Wong** and **J. Bokor**, "Ultrafast Electrical Switching for Magnetic Random Access Memory," *IEEE International Electron Devices Meeting*, San Francisco, CA, Dec 2017.
27. S. Kim, P. Zheng, K. Kato, L. Rubin, **T.-J. K. Liu**, “Cost-Efficient Sub-lithographic Patterning with Tilted-Ion Implantation (TII),” INVITED; to be presented at the *2018 International Symposium on VLSI Technology, Systems, and Applications (2018 VLSI-TSA)* (Hsinchu, Taiwan), April 2018. (Submitted)
28. 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," *International Magnetics Conference (Intermag)*, Singapore, Apr 2018. (Submitted)
29. K. Han, S.A. Fortuna, M. Amani, S. Desai, D.-H. Lien, G.H. Ahn, **E. Yablonovitch**, **A. Javey**, **M.C. Wu**, "Bright electroluminescence from single back gate WSe2 p-n junctions using pulsed injection," *Conference on Lasers and Electro-Optics (CLEO)*, San Jose, CA, May 2018. (Submitted)

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

1. J.A. del Alamo, “Integrated Microelectronics Devices: Physics and Modeling,” Pearson, 2017 (850 pages).

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

N/A

1b. Conference Presentations (in alphabetical order)

Talks: *(does not include 2017 talks that have published proceedings by 12/31/2017;* *see pp. 112-114)*

1. B. Saha, A. Peschot, B. Osoba, C. Ko, T.-J. K. Liu and J. Wu, “Reduction of contact adhesion energy in NEM relays by ion-beam synthesized oxide nanolayers,” *2016 Fall MRS Meeting*, Boston, Massachusetts, December 2016.
2. J. Kong, “Chemical vapor deposition synthesis and transfer of two dimensional materials,” *MRS Fall Meeting*, Boston, Massachusetts, December 2016 (Invited).
3. S. Louie, “Novel Quantum Phenomena in Atomically Thin One- and Two-dimensional Materials,” *Joint Hong Kong University of Science & Technology – Nanjing University (HKUST-NJU) Workshop on Quantum Materials*, Hong Kong, December 2016 (Invited).
4. S. G. Louie, “Novel Quantum Phenomena in Atomically Thin Two-Dimensional Materials: Theoretical Studies,” *International Symposium on Advanced Materials and Biophysics, Institute of Atomic and Molecular Sciences*, Taipei, Taiwan, January 2017 (Invited).

5. S. Louie, “Novel Phenomena in Quasi Two-Dimensional Materials: A Theoretical Perspective,” *10th International Conference on Computational Physics (ICCP10)*, Macau, China, January 2017 (Invited).
6. T.-J. K. Liu, “There’s Plenty of Room at the Top,” *30th IEEE Conference on Micro Electro Mechanical Systems*, Las Vegas, Nevada, January 2017.
7. H.-S. P. Wong, “The N3XT Technology for Brain-Inspired Computing,” *SPIE Advanced Lithography Symposium*, San Jose, CA, February 2017 (Invited).
8. H.-S. P. Wong, “Memory – the N3XT Frontier,” *8th Annual Non-Volatile Memories Workshop*, La Jolla, California March 2017(Invited).
9. J.A. del Alamo, “Refining the III-V FinFET,” *CS-International Conference*, Brussels, Belgium, March 2017 (Invited).
10. A. Javey, “2D Semiconductor Electronics: Advances, Challenges and Opportunities,” *APS Spring Meeting*, New Orleans, Louisiana, March 2017.
11. S. G. Louie, “Excited States and Optical Spectra Based on GW-BSE: Dimensionality and Screening,” *2017 American Physical Society (APS) Annual March Meeting*, New Orleans, Louisiana, March 2017 (Invited).
12. T. Cao, “Topological phases in graphene nanoribbons,” *American Physical Society (APS) March Meeting 2017*, New Orleans, Louisiana, March 2017.
13. F. Zhao, “Electronic Structure of Boron-doped Graphene Nanoribbons on Metallic Substrates: Ab Initio Studies and Scanning Probe Measurements,” *American Physical Society (APS) March Meeting 2017*, New Orleans, Louisiana, March 2017.
14. F. Niroui, M. Saravanapavanantham, T. M. Swager, J. H. Lang, and V. Bulović, “Engineering nanoscale structures with nanometer precision and surface uniformity for plasmonic devices,” *Podium Presentation, Materials Research Society Conference*, Phoenix, Arizona, March 2017.
15. J. Wu, “Smart applications of phase transition materials in micro-actuation,” *Materials Research Society Spring 2017 Meeting*, Phoenix, Arizona, April 2017.
16. S. Louie, “Novel Quantum Phenomena in Atomically Thin Two-dimensional Materials,” *Materials Research Society (MRS) Spring Meeting*, Phoenix, Arizona, April 2017 (Invited).
17. A. Javey, “2D Semiconductor Electronics: Advances, Challenges and Opportunities,” *MRS Spring Meeting*, Phoenix. Arizona, April 2017.
18. J.A. del Alamo, “III-V Channel Transistors,” *International Symposium on VLSI Technology, Systems and Applications (VLSI-TSA*), Hsinchu, Taiwan, April 2017 (Invited).
19. H.-S. P. Wong, “The N3XT 1,000X of Computing Energy Efficiency,” *Materials Research Society (MRS) Spring Meeting, Symposium ED9: Advanced Interconnects for Logic and Memory Applications—Materials, Processes and Integration*, Phoenix, Arizona, April 2017 (Invited).
20. J.A. del Alamo, “Nanometer-scale III-V CMOS,” *PQI 2017: Quantum Revolutions*, Pittsburgh Quantum Institute, Pittsburg, Pennsylvania, April 2017 (Invited).
21. F. Schuster, J. Kapraun, G. Malheiros-Silveira, S. Deshpande, and C. Chang-Hasnain, “Lasing of Site-Controlled InGaAs/InP Quantum Well Nanopillars Grown on Silicon,” *CLEO*, May 2017.
22. X. Zhao, C. Heidelberger, E. A. Fitzgerald and J. A. del Alamo, “Top-Down InGaAs Vertical Nanowire MOSFETs with Record Characteristics,” *Compound Semiconductor Week*, Berlin, Germany, May 2017.
23. A. Javey, “2D Semiconductor Electronics: Advances, Challenges and Opportunities,” *ICMED*, May 2017.

24. A. Vardi, J. Lin, W. Lu, X. Zhao and J. A. del Alamo, “A Si-Compatible Fabrication Process for Scaled Self-Aligned InGaAs FinFETs,” *Compound Semiconductor Manufacturing Technology Conference (CS MANTECH*), Indian Wells, California, May 2017 (Invited).
25. L. Marlor and C. Amelink, “A Follow Up Study on the Impact of Summer Research Experiences on Community College Students Career Paths,” *American Society for Engineering Education*, Columbus, Ohio, June 2017.
26. F. Fischer, “Engineering Quantum Confinement Effects in Organic Nanostructures,” *Physical Organic Chemistry Gordon Research Conference*, Holderness, New Hampshire, June 2017.
27. J.A. Incorvia, “Three-terminal spin switches for logic and memory,” *Western Digital Seminar*, San Jose, California, June 2017 (Invited).
28. F. Fischer, “Engineering Quantum Confinement Effects in Organic Nanostructures,” *International Symposium on Novel Aromatics*, Stony Brook, New York, July 2017.
29. E. Yablonovitch, “The Scientific Challenge of Replacing the Transistor by Optical Communications,” *IEEE Photonics Society Summer Topicals LEIN*, San Juan, Puerto Rico, July 2017.
30. E. Yablonovitch, “Optical Antennas; Spontaneous Emission Faster Than Stimulated Emission,” *8th Int'l. Conf. on Metamaterials, Photonic Crystals and Plasmonics*, Incheon Korea, July 2017.
31. V. Stojanovic, “Opportunities for Integrated Nanophotonics: From Across Data-Centers to Connecting Logic Gates,” *IEEE Photonics Society Summer Topicals Meeting Series*, San Juan, Puerto Rico, July 2017(Invited).
32. J.A. del Alamo, “Nanometer-Scale III-V 3D MOSFETs?,” *4th International Atomic Layer Etching Workshop*, Denver, Colorado, July 2017 (Invited).
33. A. Javey, “2D Semiconductor Electronics: Advances, Challenges and Opportunities,” *OSA*, July 2017.
34. A. Javey, “2D Semiconductor Electronics: Advances, Challenges and Opportunities,” *ARL Workshop on 2D Materials*, July 2017.
35. S. G. Louie, “Band Topological Effects in 1D and 2D Materials: Graphene Nanoribbons and Few-layer Graphene System,” *New Trends in Topological Insulators 2017 (NTTI 2017) Conference*, Ascona, Switzerland. July 2017(Invited).
36. H.-S. P. Wong, “The N3XT 1,000× of Computing Energy Efficiency,” *1st International Semiconductor Conference for Global Challenges (ISCGC)*, Nanjing, China, July 2017(Invited).
37. S. G. Louie, “Interaction Effects in Atomically Thin Two-Dimensional Materials,” *7th International Conference on Nanoscience & Technology (ChinaNANO 2017)*, Beijing, China. August 2017(Invited).
38. S.G. Louie, “The Fascinating Quantum World of Two-dimensional Materials: Interaction and Topological Effects,” *National Center for Theoretical Sciences (NCTS) 20th Anniversary Symposium, Frontiers in Physics*, Hsinchu, Taiwan. August 2017 (Invited).
39. A. Javey, “2D Semiconductor Electronics: Advances, Challenges and Opportunities,” *2D Semiconductor Workshop at EPFL*, August 2017.
40. S.G. Louie, “Quantum Phenomena in Atomically Thin Two-Dimensional Materials,” *2017 September Meeting of nanoGe – International Symposium on Optoelectronics of 2-D Nanostructured Semiconductors: Parabolic vs. Linear Dirac Bands*, Barcelona, Spain. September 2017 (Invited).
41. E. Acosta, A. Vidana, M. Martinez, S. Almeida, J. Mireles, and D. Zubia, “Development of Fabrication Process of Comb-Drive Electrostatic Actuator MEMS to Study the Strain Mechanism in Two-Dimensional Transitional Metal Dichalcogenides,” *Oral Talk*, *X*

International Conference on Surfaces, Materials and Vacuum, Ciudad Juarez, Mexico, September 2017.

42. A. Vidaña, M. Martinez, E. Acosta, S. Almeida, J. Mireles, and D. Zubia, "Analytical and Simulation Study of Conduction Modulation of MoS2 via Strain using Comb-Drive Electrostatic Actuators," *Oral Talk, X International Conference on Surfaces, Materials and Vacuum*, Ciudad Juarez, Mexico, September 2017.
43. J.A. del Alamo, "Extending the Era of Moore's Law through Materials Innovation," *SEMI Strategic Materials Conference*, San Jose, California, September 19, 2017.
44. S.G. Louie, "Interaction and topological effects in the photophysics of two-dimensional material*," CECAM International Workshop on* "*Charge carrier dynamics in nanostructures: optoelectronic and photo-stimulated processes*," Bremen, Germany. October 2017(Invited).
45. H.-S. P. Wong, "Reaching for the N3XT 1,000× of Computing Energy Efficiency," *Chinese American Information Storage Society (CAISS) 22nd Annual Conference and Banquet*, October 2017.
46. J. Bokor, "Ultrafast Charge Current Induced Magnetization Reversal in GdFeCo," *Ultrafast Magnetism Conference*, Kaiserslautern, Germany, October 2017 (Invited).
47. A. Pattabi, J. Gorchon, C-H. Lambert, Y. Yang, R. Wilson, S. Salahuddin, and J. Bokor, "Single-shot ultrafast all-optical magnetization switching of ferromagnetic Co/Pt multilayers," *Ultrafast Magnetism Conference*, Kaiserslautern, Germany, October 2017.
48. J. Bokor, "Prospects for Ultrafast (<10 psec) MRAM," *5th Berkeley Symposium on Energy Efficient Electronics Systems*, Berkeley, CA, October 2017 (Invited).
49. J.A. del Alamo, X. Cai, J. Lin, W. Lu, A. Vardi, and X. Zhao, "CMOS beyond Si: Nanometer-Scale III-V MOSFETs," *31st Annual IEEE Bipolar/BiCMOS Circuits and Technology Meeting*, Miami, FL, October 2017 (Invited).
50. J.A. del Alamo, X. Zhao, W. Lu, and A. Vardi, "Towards Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs and TFETs," 5th Berkeley Symposium on Energy Efficient Electronics Systems, Berkeley, CA, October 2017 (Invited).
51. F. Fischer, "Graphene Nanoribbon Band Gap Engineering: Orbitally Matched vs. Substitutional Doping," *5th Berkeley Symposium on Energy Efficient Electronics Systems*, Berkeley, CA, October 2017.
52. H.-S. P. Wong, "The N3XT Technology for Brain-Inspired Computing," *IEEE SOI-3D-Subthreshold Microelectronics Technology Unified Conference (S3S)*, San Francisco, CA, October 2017 (Invited).
53. C.-H. Lambert, J. Gorchon, Y. Yang, A. Pattabi, R. Wilson, S. Salahuddin, and J. Bokor, "Single shot ultrafast all optical magnetization switching of ferromagnetic Co/Pt multilayers," *62nd Annual Conference on Magnetism and Magnetic Materials*, Pittsburgh, Pennsylvania, November 2017.
54. J. Bokor, "Ultrafast Charge Current Induced Magnetization Reversal in Only 10 psec," *62nd Annual Conference on Magnetism and Magnetic Materials*, Pittsburgh, Pennsylvania, November 2017 (Invited).
55. S.G Louie, "Magnetism in Atomically Thin 2D van der Waals Crystals," *62nd Annual Conference on Magnetism and Magnetic Materials*, Pittsburgh, Pennsylvania, November 2017(Invited).
56. S. G. Louie, "Topological Effects in the Electronic and Optical Properties of Atomically Thin 2D Materials," *7th International Workshop on Quantum Energy*, Haikou, Hainan, China. November 2017 (Invited).

57. H.-S. P. Wong, “On to the Next Fifty Years – Guideposts from the Past Fifty Years,” *Semiconductor Integrated Circuit Technology Workshop*, Zhejiang University, Hangzhou, China, November 2017 (Invited).
58. H.-S. P. Wong, “Reaching for the N3XT 1,000× of Computing Energy Efficiency,” *Semiconductor Integrated Circuit Technology Workshop*, Zhejiang University, Hangzhou, China, November 2017 (Invited).
59. J. A. Incorvia, “Spin and Valley Hall Effect in Monolayer WSe2 Transistors at Near-Room Temperature controlled via Electric Field,” *Magnetism and Magnetic Materials Conference*, November 2017.

Posters

1. X. Zhao, A. Vardi, and J. A. del Alamo, “III-V Vertical Nanowire Transistor for Ultra-Low Power Applications,” *MTL Annual Research Conference*, Bretton Woods, New Hampshire, January 2017.
2. F. Fischer, “Functional Conjugated Polymers through Ring-Opening Alkyne Metathesis,” *Polymer Gordon Research Conference*, Mt. Holyoke College, June 2017.
3. J.A. Incorvia, “Near-room temperature electrical control of spin and valley Hall effect in monolayer WSe2 transistors for spintronic applications,” *IEEE International Conference on Nanotechnology*, Pittsburgh, Pennsylvania, July 2017.
4. F. Fisher, “Exploring and Controlling Quantum Confinement Effects in Atomically Defined Graphene Nanoribbons,” *David and Lucile Packard Meeting*, Monterey, California, September 2017.
5. M. Martinez, A. Vidaña, E. Acosta, S. Almeida, J. Mireles, and David Zubia, “Simulated Novel Comb-Drive Micro-Electro-Mechanical Actuators Intended for Mechanical Strain of 2D-Layered MoS2,” *X International Conference on Surfaces, Materials and Vacuum*, Ciudad Juarez, Mexico, September 2017.
6. 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.
7. N. Andrade, S.A. Fortuna, K. Han, S. Hooten, E. Yablonovitch, and M. Wu, “Efficient Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based nanoLED," *IEEE Photonics Society Conference*, Orlando, California. October 2017.
8. N. Andrade, S.Fortuna, K. Han, S. Hooten, E. Yablonovitch, and M. Wu, “Efficient and Broadband Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based nanoLED,” *IEEE SOI-3D-Subthreshold Microelectronics Technology Conference (IEEE S3S)*, San Francisco, California. October 2017.
9. N. Andrade, S. Fortuna, K. Han, S. Hooten, E. Yablonovitch, and M. Wu, “Efficient and Broadband Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based nanoLED,” 5th *Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop*, Berkeley, California. October 2017.
10. A. El-Ghazaly, D. O’Mahoney, C. H. Lambert, J. Gorchon, P. Brown, A. Pattabi, H.-S. P. Wong and J. Bokor, “Ultrafast Magnetic Memory Bits Using All-Optical Magnetic Switching,” 5th

Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop, Berkeley, California, October 2017.

11. A. Pattabi, J. Gorchon, C.-H. Lambert, Y. Yang, R. Wilson, S. Salahuddin, and J. Bokor, “Single-shot ultrafast all-optical magnetization switching of ferromagnetic Co/Pt multilayers,” *IEEE SOI-3D-Subthreshold Microelectronics Technology Conference (IEEE S3S)*, San Francisco, California, October 2017.
12. A. Pattabi, J. Gorchon, C.-H. Lambert, Y. Yang, R. Wilson, S. Salahuddin, and J. Bokor, “Single-shot ultrafast all-optical magnetization switching of ferromagnetic Co/Pt multilayers,” 5th *Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop*, Berkeley, California, October 2017.
13. P. Zhao, “Measuring the Edge Recombination Velocity of Monolayer Semiconductors,” *IEEE SOI-3D-Subthreshold Microelectronics Technology Conference (IEEE S3S)*, San Francisco, California, October 2017.
14. M. Amani, “High Photoluminescence Quantum Yield in Transition Metal Dichalcogenides Enabled by Superacid Treatmennt,” *IEEE SOI-3D-Subthreshold Microelectronics Technology Conference (IEEE S3S)*, San Francisco, California, October 2017.
15. U. Sikder and T.-J. K. Liu, “Design optimization for NEM relays implemented in BEOL layers,” *IEEE SOI-3D-Subthreshold Microelectronics Technology Conference (IEEE S3S)*, San Francisco, California. October 2017.
16. Z. Ye, H. Kam and T.-J. K. Liu, “Negative stiffness structures for energy efficient MEM switches,” 5th *Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop*, Berkeley, CA, October 2017.
17. F. Zhao, T. Cao, Y.-L. Lee, and S.G. Louie, “Designing Graphene Nanoribbon Transistors for Future Electronics,” 5th *Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop*, Berkeley, CA, October 2017.
18. S. Almeida, D. Zubia, A. Vidaña, and Mariana Martinez, “Conductance Modulation in 2D Materials by NEMS for Lower-Power Applications,” 5th *Berkeley Symposium on Energy Efficient Electronic Systems and Steep Transistors Workshop*, Berkeley, California, October 2017.
19. P. Brown, A. El-Ghazaly and J. Bokor, “Measuring the Anomalous Hall Effect on Gdfeco Nanodots Using All-Optical Switching,” *2017 SACNAS Annual Conference*, Salt Lake City, Utah, October 2017.
20. D. O’ Mahoney, A. El-Ghazaly and J. Bokor, “Characterization of Ultrafast Switching Behavior with Scaling of Gd-Co Nonmagnetic Dots,” *2017 SACNAS Annual Conference*, Salt Lake City, Utah, October 2017.
21. N. Suguitan, S. Wu, and J. Bokor, “A Study of the Effects of Substrate Choice on Monolayer and Fewlayer NbSe2,” *2017 SACNAS Annual Conference*, Salt Lake City, Utah, October 2017.
22. A. Perlas, Z. Ye, and T.-J. K. Liu, “Characterization of Low-Voltage Micro-Electro-Mechanical Relay Integrated Circuits,” *2017 SACNAS Annual Conference*, Salt Lake City, Utah, October 2017.
23. D. O’ Mahoney, A. El-Ghazaly and J. Bokor, “Characterization of Ultrafast Switching Behavior with Scaling of Gd-Co Nonmagnetic Dots,” *NOBCCHe*, Minneapolis, Minnesota, October 2017.

24. A. El-Ghazaly, C.-H. Lambert, J. Gorchon, A. Pattabi, H.-S. P. Wong and J. Bokor, "Ultrafast Magnetic Memory for Higher Data Rates and Smarter Cities," *Arab American Frontiers of Science, Engineering and Medicine Symposium*, Rabat, Morocco, November 2017.

1c. Other Dissemination Activities (in chronological order)

1. F. Fischer, "Quantum Confinement in Organic Nanostructures," *E3S Solid State Devices Seminar*, Berkeley, California, February 2017.
2. A. Javey, "2D Semiconductor Electronics: Advances, Challenges and Opportunities," *2D Workshop*, University of Central Florida, February 2017.
3. E. Yablonovitch, "What Does the Clock Speed of My Computer Have to do With the Fundamental Constants of Nature, h, c, q, m?," *The Lawrence Workshop on Solid-State Technology*, ASU, Tempe, Arizona, February 23, 2017.
4. J.A. del Alamo, "Still Plenty of Room at the Bottom," *ASML Technology Symposium*, San Jose, California, February 27, 2017.
5. S.G. Louie, "Addressing Dirac's challenge: Novel quantum phenomena in bulk and reduced-dimensional materials," *Göteborg Mesoscopic Lecture at the Chalmers University of Technology*, Gothenburg, Sweden, March 2017 (Invited).
6. F. Fischer, "Design, Synthesis and Exploitation of Quantum Confinement in Organic Nanostructures," *Max-Planck Meeting on Molecular Nanosystems, Ascona*, Switzerland, March 2017.
7. H.-S. P. Wong, "The N3XT 1,000× of Computing Energy Efficiency," *UC Berkeley Wireless Research Center (BWRC)*, UC Berkeley, Berkeley, California, March 10, 2017.
8. J.A. del Alamo, "Extending Moore's Law through III-V Compound Semiconductors," *Ben Gurion University*, Be'er Sheva, Israel, March 27, 2017.
9. J.A. del Alamo, "Extending Moore's Law through III-V Compound Semiconductors," *Vincent Meyer Colloquium Technio*n, Haifa, Israel, March 29, 2017.
10. J. Bokor, "Ultrafast Spintronics," *UT Austin ECE Seminar*, April 2017.
11. E. Yablonovitch, "Spontaneous Emission Fundamentally Faster than Stimulated Emission*?*" *U. Arizona Seminar*, Tucson, Arizona, April 18, 2017.
12. S.G. Louie, "Novel Quantum Phenomena in Atomically Thin Two-dimensional Materials," *Franklin Institute Medals Symposium*, Philadelphia, Pennsylvania, May 2017 (Invited).
13. S.G. Louie, "Novel Quantum Phenomena in Atomically Thin 2D Materials," Université Pierre et Marie Curie, Paris, France, May 2017 (Invited).
14. J.A. Currivan-Incorvia and H.-S.P. Wong, "Next generation computing using spin-based and 2D materials," *Caltech Young Investigators Seminar Series*, Pasadena, California, May 2017.
15. E. Yablonovitch, "The Scientific Challenge of Replacing the Transistor with a Lower Voltage Device," *Center for Nano-Scale Materials Users Meeting*, Argonne National Lab, Lemont, IL, May 7, 2017.
16. H.-S. P. Wong, "Memory – the N3XT Frontier," *Western Digital*, San Jose, CA. May 15, 2017.
17. J.A. del Alamo, "There's Plenty of Room at the Bottom – and at the Top," *ACM-W Distinguished Speaker Seminar*, University of California, Los Angeles, Los Angeles, California, May 18, 2017.
18. J.A. Currivan-Incorvia, Y. Kang, N. Roschewsky, C.-H. Lambert, B. Eryilmaz, W. Wan, V. Stojanovic, S. Salahuddin, and H.-S.P. Wong, "Non-volatile hybrid CMOS-MRAM circuits

using three-terminal spin orbit torque switches for normally-off computing," *Center for Memory and Recording Research*, San Diego, California, May 19, 2017.

19. J.A. del Alamo, "Still Plenty of Room at the Bottom," *Intel Mask Operations, Intel Corporation*, Santa Clara, California, June 1, 2017.
20. H.-S. P. Wong, "Memory – the N3XT Frontier," *Panasonic*, Osaka, Japan. June 5, 2017.
21. E. Yablonovitch, "The Scientific Challenge of Replacing the Transistor with a Lower Voltage Device," Beyond CMOS: From Devices to Systems, Technion, Haifa, Israel, June 5, 2017.
22. H.-S. P. Wong, "Memory: the Key to Attaining the N3XT 1,000× of Computing Energy Efficiency," *Toshiba Memory Company*, Yokkaichi, Japan, June 9, 2017.
23. E. Yablonovitch, "The Optical-Antenna LED; Faster than the LASER," *Tel Aviv University Seminar*, Tel Aviv, Israel, June 11, 2017.
24. J.A. del Alamo, "Still Plenty of Room at the Bottom – and at the Top," *Applied Materials, Inc.*, Santa Clara, California, June 13, 2017.
25. H.-S. P. Wong, "High Impact Research," *Department of Applied Physics Retreat*, The Hong Kong Polytechnic University, June 22, 2017.
26. H.-S. P. Wong, "Reaching for the N3XT 1,000× of Computing Energy Efficiency," *Peking University*, Beijing, China, July 20, 2017.
27. S.G. Louie, "The Fascinating Quantum World of Two-dimensional Materials: Interaction and Topological Effects," *MARVEL Distinguished Lecture at the École Polytechnique Fédérale de Lausanne (EPFL)*, Lausanne, Switzerland, July 2017 (Invited).
28. S.G. Louie, "The Fascinating Quantum World of Two-dimensional Materials: Interaction and Topological Effects," *Zhong Guan Cun Forum on Condensed Matter Physics at the Institute of Physics of the Chinese Academy of Sciences*, Beijing, China, August 2017 (Invited).
29. F. Fischer, "Engineering Quantum Confinement Effects in Organic Nanostructures,"
30. *Graphene Week*, Athens, Greece, September 2017.
31. E. Yablonovitch, "What's Next for Electronics Research, After Moore's Law?," *Sandia National Lab Seminar*, Albuquerque, New Mexico, September 12, 2017.
32. E. Yablonovitch, "The Optical-Antenna LED, Faster than the LASER," *Symposium: 20 years of Nano-Photonics*, Erlangen, Germany, September 21, 2017.
33. S. G. Louie, "The Fascinating Quantum World of Two-dimensional Materials: Symmetry, Interaction and Topological Effects," *H.C. Ørsted Lecture at the Technical University of Denmark*, Copenhagen, Denmark, October 2017 (Invited).
34. E. Yablonovitch, "Why We Need to Replace the Transistor, and What Would be the Newly Required Material Properties?" *NSF Center for Integrated Quantum Materials Annual Retreat*, Medford, Massachusetts, October 12, 2017.
35. H.-S. P. Wong, "Rising from Stagnation – Beyond 5 nm in the 21st Century," *DARPA Microsystems Exploratory Council (MEC) Reinventing Fabrication Workshop*, Albany, New York, October 23, 2017 (Invited).
36. H.-S. P. Wong, "Reaching for the N3XT 1,000× of Computing Energy Efficiency," *MIT*, Boston, Massachusetts, October 25, 2017 (Invited).
37. S.G. Louie, "Novel Optical Selection Rules, Topological Phases, and Tunable Magnetism in 2D Materials," *Fudan University*, Shanghai, China, November 2017 (Invited).
38. F. Fischer, "Engineering Quantum Confinement Effects in Organic Nanostructures," *Chemistry Seminar*, Columbia University, November 2017.

2. *Awards & Honors*

Recipient	Reason for Award	Award Name	Sponsor	Date	Award Type
Ming C. Wu	Research in optical MEMS	William Streifer Scientific Achievement Award	IEEE Photonics Society	Oct 2016	Scientific
Tsu-Jae King Liu	Contributions in education and research	ISDRS 2016 Aldert van der Ziel award	IEEE	Dec 2016	Scientific
Tsu-Jae King Liu	Technical Achievements	Membership in National Academy of Engineering	National Academy of Engineering	Feb 2017	Scientific
J. A. del Alamo		Vincent Meyer Colloquium	Technion	Mar 2017	Scientific
Raymond Blackwell		NSF Graduate Fellowship	NSF	Mar 2017	Scientific
Zhixin Alice Ye	Academic Excellence	Postgraduate Scholarship-Doctoral	Natural Sciences and Engineering Research Council (Canada)	Mar 2017	Scientific
Jane Edgington	Education	Goldwater Scholarship	Goldwater foundation	Mar 2017	Scientific
Junqiao Wu	Research	Bakar Faculty Fellowship	Bakar Foundation	Apr 2017	Scientific
Wenjie Lu	Best student paper	Best student paper	Compound Semiconductor Week	May 2017	Scientific
Jean Anne Incorvia		Caltech Young Investigator Lecturer in Engineering	Caltech	May 2017	Scientific
Felix Fischer		Journal of Physical Organic Chemistry Award for Early Excellence	Journal of Physical Organic Chemistry	Jun 2017	Scientific
Steven G. Louie	Scientific Achievement	Fall 2017 H. C. Ørsted Lecturer	Technical University of Denmark	Jul 2017	Scientific
Vladimir Bulovic	MIT thin film solar cells	Materials, Resources & Water Category	Katerva	Jul 2017	Scientific
Amal El-Ghazaly		Presidential postdoctoral fellowship	University of California	Jul 2017	Scientific
Wenjie Lu	Best student paper	Best student paper	Techcon	Sept 2017	Scientific
Sakhrat Khizroev	An industry award of $375,000: to	Industry-standard Testing of Primary	Turning Point Brands	Sept 2017	Scientific

	comparatively study primary and secondary battery cells based on magnetoelectric nanoparticles and other approaches	and Secondary Battery Cells for Niche Applications			
Ming C. Wu	Invention of optoelectronic tweezers	C.E.K. Mees Medal	Optical Society of America	Sept 2017	Scientific
Ming C. Wu	Contributions to Optical MEMS	MOC Award	Micro-Optics Conference	Nov 2017	Scientific
Eli Yablonovitch	For leadership, innovations, and entrepreneurial achievements in photonics, semi-conductor lasers, antennas, and solar-cells.	IEEE Edison Medal	IEEE	Nov 2017	Scientific
Timothy Swager		Chandler Medal	Columbia University Department of Chemistry	Dec 2017	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)

4a. General Outputs of Knowledge Transfer Activities

Patents:

Patent Name	Inventors/Authors	Number	Application Date	Receipt Date
Instantly rechargeable battery	S. Khizroev and R. Guduru	Filed with FIU	May 2, 2017	
Two-dimensional patterning of integrated circuit layer by tilted ion implantation	T.-J. K. Liu, F.Ding, and Y.-T. Wu	U.S. Provisional Application No. 62/513,104	May 31, 2017	
Growth of transition metal dichalcogenide layers from corresponding metal powders	Q. Ji, Z. Gao, and Jing Kong		Disclosure filed, application In progress	
Writing of a Magnetic Memory with Picosecond Electrical Pulses	Y. Yang, J. Gorchon, R. Wilson, C.-H. Lambert, S. Salahuddin, and J.Bokor		Disclosure filed, application In progress	
Single Shot Ultrafast All Optical Magnetization Switching of Ferromagnetic Layers	J. Gorchon, J. Bokor, S. Salahuddin, C.-H. Lambert, Y. Yang, R. Wilson, and A. Pattabi		Disclosure filed, application In progress	

4b. Other Outputs of Knowledge Transfer Activities

a. Philip Wong had multiple visits with Google, ASML, IMEC, Microsoft, Applied Materials, Lam Research, Toshiba, Panasonic, Western Digital, UC Berkeley BWRC, TSMC.

b. David Zubia has started a collaboration with Prof. Jose Mireles from the Universidad Autonoma de Ciudad Juarez, Mexico, who is an expert in MEMS design and fabrication.

5a. Participants

In the current reporting period, the Center has 125 participants. Funding of faculty, postdoctoral, graduate student, and undergraduate student participants is summarized as follows.

Period 8	**Summer**	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	14	1	0	5	20

	Funded by E3S			**Other Funding Source**	**Total Participants**
Category	50% or more	Less than 50%	**Total**		
Postdocs	10	2	**12**	0	**12**
Grad Students	24	9	**33**	10	**43**
Undergrads	1	24	**25**	1	**26**
TOTAL					**81**

PARTICIPANTS - PERIOD 8

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
20	Faculty	10	Berkeley	18	E.E.	17	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	14	US Citizens
		7	MIT	1	Mats Sci	3	F	0	Visual Impairment	16	Not Hispanic or Latino	6	Asian	6	Permanent Resident
		1	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	3	Decline to State	0	Black or African American	0	Other non-US Citizen
		1	UTEP	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			18	None			12	White	0	Not Available
		1	FIU	0	Other			2	Decline to State			2	Decline to State		
		0	Other					0	Not Available			0	Not Available		
12	Postdocs	9	Berkeley	9	E.E.	9	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	2	US Citizens
		1	MIT	0	Mats Sci	3	F	0	Visual Impairment	8	Not Hispanic or Latino	5	Asian	2	Permanent Resident
		1	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	4	Other non-US Citizen
		1	UTEP	1	Chemistry			0	Other	3	Not Available	1	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	1	ME			12	None			6	White	4	Not Available
				0	Other			0	Decline to State			0	Decline to State		
								1	Not Available			0	Not Available		
43	Graduate Students	30	Berkeley	30	E.E.	37	M	0	Hearing Impairment	3	Hispanic	1	American Indian or Alaskan Native	20	US Citizens
		8	MIT	4	Mats Sci	6	F	0	Visual Impairment	39	Not Hispanic or Latino	25	Asian	2	Permanent Resident
		2	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	2	Black or African American	18	Other non-US Citizen
		1	UTEP	6	Chemistry			0	Other	3	Not Available	0	Native Hawaiian or Other Pacific Islander	3	Decline to State
		2	FIU	1	ME			40	None			15	White	6	Not Available
				2	Other			3	Decline to State			2	Decline to State		
								3	Not Available			0	Not Available		
37	Undergraduate Students	2	Berkeley	12	E.E.	21	M	0	Hearing Impairment	11	Hispanic	0	American Indian or Alaskan Native	30	US Citizens
		1	MIT	0	Mats Sci	16	F	0	Visual Impairment	24	Not Hispanic or Latino	9	Asian	5	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	2	Decline to State	4	Black or African American	0	Other non-US Citizen
		2	UTEP	5	ChemE			0	Other	0	Not Available	1	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	4	ME			36	None			10	White	2	Not Available
		32	Other	15	Other			1	Decline to State			3	Decline to State		
								0	Not Available			10	Not Available		
9	Staff	8	Berkeley	8	E3S	3	M	0	Hearing Impairment		Hispanic	1	American Indian or Alaskan Native	8	US Citizens
		1	MIT	2	OEOP	6	F	0	Visual Impairment	8	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	5	TAP			0	Mobility/Orthopedic Impairment	0	Decline to State	4	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC					9	None			4	White	1	Not Available
									Decline to State			0	Decline to State		
								0	Not Available			1	Not Available		
4	Visting Scholar	0	Berkeley	0	E.E.	2	M	0	Hearing Impairment	0	Hispanic or Lantino	0	American Indian or Alaskan Native	3	US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	3	Not Hispanic or Latino	1	Asian	6	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	1	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			3	None			1	White	1	Not Available
		0	FIU	4	Other			1	Decline to State			1	Decline to State		
		4	Other					0	Not Available			0	Not Available		
125	**TOTAL PARTCIPANTS**														

5b. Affiliates

AFFILIATES - PERIOD 8

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
1	Faculty	0	Berkeley	0	E.E.	0	M	0	Hearing Impairment	0	Hispanic or Lantino	0	American Indian or Alaskan Native	1	US Citizens
		0	MIT	0	Mats Sci	1	F	0	Visual Impairment	1	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	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			1	None			0	White	0	Not Available
		1	CCC	0	Other			0	Decline to State			0	Decline to State		
		0	Other					0	Not Available			1	Not Available		
5	Research Scientists & Visiting Scholar	1	Berkeley		E.E.	5	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native		US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	1	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	4	Other			0	Other	4	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU					1	None			0	White	5	Not Available
		4	Other					4	Not Available			5	Not Available		
10	Postdocs	7	Berkeley	9	E.E.	8	M	0	Hearing Impairment	1	Hispanic	1	American Indian or Alaskan Native	1	US Citizens
		3	MIT	0	Mats Sci	2	F	0	Visual Impairment	3	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	3	Other non-US Citizen
		0	UTEP	0	Chemistry			0	Other	6	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	0	ME			4	None			2	White	6	Not Available
				1	Other			0	Decline to State			0	Decline to State		
								6	Not Available			6	Not Available		
14	Graduate Students	5	Berkeley	11	E.E.	13	M		Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	2	US Citizens
		4	MIT	0	Mats Sci	1	F		Visual Impairment	5	Not Hispanic or Latino	3	Asian	0	Permanent Resident
		0	Stanford	2	Physics				Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	3	Other non-US Citizen
		0	UTEP	0	Chemistry				Other	9	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		5	FIU	0	ME			5	None			1	White	9	Not Available
				1	Other			0	Decline to State			0	Decline to State		
								9	Not Available			9	Not Available		
9	Undergraduate Students	7	Berkeley	6	E.E.	7	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	0	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	1	ChemE			0	Other	9	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	FIU	0	ME			0	None			0	White	9	Not Available
		1	Other	1	Other			0	Decline to State			0	Decline to State		
								9	Not Available			9	Not Available		

	Category		Institutional		Department		Gender		Disability Status		Ethnicity		Race		Citizenship
TBD (x)	Pre-College Students	0	Berkeley	0	E.E.	x	M	0	Hearing Impairment	x	URM	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	x	F	0	Visual Impairment	x	Non-URM	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment			0	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Other			0	Other			0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	x	N/A			0	None			0	White	x	Not Available
		0	CCC					0	Decline to State			0	Decline to State		
		x	Other					x	Not Available			x	Not Available		
7	Staff	4	Berkeley	0	E3S	2	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	6	US Citizens
		3	MIT	2	OEOP	5	F	0	Visual Impairment	5	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	4	TAP			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC					6	None			3	White	1	Not Available
								0	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
46	**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.	Lockheed Martin	Company	San Francisco, CA	Robert Fernandez	Research Collaboration	Yes
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.	ARM	Company	Austin, Texas	Greg Yeric	Research Collaboration	Yes
6.	ASML	Company	Veldhoven, Netherlands	Nak Seong	Research Collaboration	Yes
7.	TSMC	Company	Hsinchu, Taiwan	Randy Osbone	Research Collaboration	Yes

8.	FLIR Systems	Company	Wilsonville, Oregon	Davey Beard	Research Collaboration	Yes
9.	Universidad Autonoma de Ciudad Juarez, Mexico	University	Juarez, Mexico	Professor Mireles	Research Collaboration	Yes
10.	Intel	Company	Hillsboro, OR, CA	Ian Young	Knowledge Transfer	No
11.	IBM	Company	Yorktown Heights, NY	Paul Soloman	Knowledge Transfer	No
12.	IMEC	Company	San Francisco, CA	Sam El Kazzi	Research	No
13.	CEA-LETI	French National Laboratory	Grenoble, France	Louis Hutin & Oliver Faynot	Education Knowledge Transfer	No
14.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Eboney Hearn	Education & Diversity	No
15.	MIT Office of the Dean of Graduate Education	University	Cambridge, MA	Gloria Anglon	Education & Diversity	No
16.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Merryl Owen	Education & Diversity	No
17.	UC Berkeley Summer Sessions	University	Berkeley, CA	Richard Russo	Education	No
18.	Berkeley Engineering Graduate Outreach	University	Berkeley, CA	Meltem Erol	Education & Diversity	No
19.	Berkeley Division of Equity and Inclusion	University	Berkeley, CA	Shaila Kotadia	Education & Diversity	No
20.	UC Berkeley Center for Teaching & Learning	University	Berkeley, CA	Richard Freishtat	Education	No
21.	Lawrence Hall of Science	Museum	Berkeley, CA	Lynn Tran	Education	No

22.	UC Berkeley School of Public Health	University	Berkeley, CA	Deborah Barnett	Education	No
23.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon	Education & Diversity	No
24.	UC Berkeley Science @ Cal	University	Berkeley, CA	Rachel Winheld	Education & Diversity	No
25.	Mathematics Engineering Science Achievement	Non-Profit	Oakland, CA	Julian Martinez	Education & Diversity	No
26.	University of California Office of the President	University	Oakland, CA	Pamela Jenkins	Diversity	No
27.	Program YoUr Future	Non-Profit	Berkeley, CA	Alankrita Dayal	Education & Diversity	No
28.	UC Berkeley Black Graduate Engineering and Science Students	University	Berkeley, CA	Benjamin Osoba	Education & Diversity	No
29.	Center for Integrated Access Networks	University	Tucson, AZ	Amee Henning	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).	14
3.	The total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC) [Leveraged funding should include both cash and in-kind support related to Center activities, but not funds awarded to individual PIs.]	$515,030
4.	The number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF).	125

8. Media Publicity of Center

1. **Multiple Honors for E3S Theme Leader, Professor Tsu-Jae King Liu, March 2017.**
   http://engineering.berkeley.edu/2017/02/3-professors-named-national-academy-engineering
   https://newsroom.intel.com/news-releases/dr-tsu-jae-king-liu-elected-to-intel-board-of-directors/
2. **Cherry Award for Center Director Yablonovitch Cherry, April 2017.**
   http://www.ieee-pvsc.org/PVSC44/awards-cherry.php
3. **Ultrafast magnetic reversal points the way toward speedy, low-power computer memory, November 2017.**
   http://news.berkeley.edu/2017/11/03/ultrafast-magnetic-reversal-points-the-way-toward-speedy-low-power-computer-memory/
4. **Eli Yablonovitch wins IEEE Edison Medal, November 2017.**
   https://eecs.berkeley.edu/topics/honors

IX. INDIRECT/OTHER IMPACTS

International Activities:

- **Elizabeth Avelar Mercado** and **Alam Figueroa Aguilar**, both undergraduate researchers with the Center, spent nine weeks at CEA-Leti, Grenoble France doing research in CMOS 3D sequential integration flow simulation and developing software to correlate data, respectively.
- **Eli Yablonovitch** received the 2018 IEEE Edison Medal for "For leadership, innovations, and entrepreneurial achievements in photonics, semiconductor lasers, antennas, and solar-cells".
- **Eli Yablonovitch** gave talks related to Spontaneous Emission and the use of Optical Antennas at various locations outside the US: Germany, Israel. This topic relates to Theme III research of the Center.
- **Steven Louie** gave talks on low-dimensional nanosystems in Sweden, Switzerland, France, and China.
- **Jesus del Alamo** gave several talks on III-V MOSFETs for CMOS: Recent Advances in Process Technology, which includes the RIE with digital etch for high aspect ratio III-V features in Isreal. The development of the REI process was funded by E3S as part of Theme I research.
- **Philip Wong** presented several talks in Japan and China on the N3XT energy-efficient computing project.

Education and Diversity:

- Impacted >35% 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 will continued on until this past period. This Site Award has been applied for renewal, and the Center is currently awaiting the decision. During the summer 2017 (Period 8), the Center hosted 15 community college students from science and engineering majors in 11 different labs on Berkeley's campus, including labs at Lawrence Berkeley National Laboratory (LBNL). These students research focused on robotics and biotechnology. Over the Center's lifespan, E^{3}S has hosted 90 community college students from 43 institutions from every region in the state of California. This total consists of projects advised by 39 faculty mentors and supervised by graduate student and postdoc mentors. Among the students eligible to transfer (excludes summer 2017 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 8, three community college faculty from electrical engineering/computer science and chemistry departments at Bay Area community colleges conducted a nine-week research experience in the UC Berkeley labs of V. Stojanovic, Durkin, and M. Wu. 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. 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 2017-2018 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 programs. This award funds students to come 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 semesters 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 8, five students 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.

- A former TTE REU student was a workstudy office assistant during this reporting period. She 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 $5.2 million and includes applying unspent funds from period 7 (~$1.8M remaining as of 03/01/17). Total unobligated funds at the end of period 8 are estimated to be $1.6M. 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.**

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 (3/1/17-2/28/18)**	**Actual Expenditure (3/1/17-10/31/17)**	**Estimates of Projected Expenditures (11/1/17-2/28/18)**
1. Eli Yablonovitch-PI	78,750	94,467	-
2. Jeffrey Bokor-Co-PI	22,607	11,341	-
3. Tsu-Jae King Liu-Co-PI	22,467	-	-
4. Steven Louie-Co-PI	12,829	4,114	-
5. Felix Fischer-Co-PI	4,054	-	-
6. (8) OTHERS	301,420	206,064	88,664
7. (13)TOTAL SENIOR PERSONNEL (1-6)	**442,127**	**315,985**	**88,664**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (7)POST DOCTORAL ASSOCIATES	400,554	269,715	93,633
2. (1)OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	6,586	4,102	1,930
3. (7)GRADUATE STUDENTS	280,836	244,053	75,383
4. (2)UNDERGRADUATE STUDENTS	13,379	22,107	7,970
5. (2)SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	128,393	88,704	45,072
6. ( )OTHER	-		
TOTAL SALARIES AND WAGES (A+B)	**1,271,875**	**944,667**	**312,653**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	450,107	313,565	123,998
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**1,721,982**	**1,258,232**	**436,651**
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)	80,975	66,893	11,642
2. FOREIGN	18,000	6,494	-
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	74,900	76,892	
2. TRAVEL	16,160	3,989	
3. SUBSISTENCE	32,925		
4. OTHER	22,762	70,217	
TOTAL NUMBER OF PARTICIPANTS (28) TOTAL PARTICIPANT COSTS	**146,747**	**151,097**	**-**
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	118,388	282,250	71,828
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	12,500	8,052	4,448
3. CONSULTANT SERVICES	20,000	9,525	10,000
4. COMPUTER SERVICES	33,362	21,278	12,084
5. SUBAWARDS	1,533,220	1,021,233	709,071
6. OTHER	169,741	9,872	
TOTAL OTHER DIRECT COSTS	**1,887,211**	**1,352,210**	**807,431**
H. TOTAL DIRECT COSTS (A THROUGH G)	**3,854,915**	**2,834,927**	**1,255,723**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	2,008,921	1,539,325	383,694
RATE:	57%	57%	57%
TOTAL INDIRECT COSTS (F&A)	**1,145,085**	**877,415**	**218,706**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**5,000,000**	**3,712,342**	**1,474,429**
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**	**3,712,342**	**1,474,429**
M. COST SHARING: PROPOSED LEVEL $ -			

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 (3/1/17-2/28/18)**	**Actual Expenditure (3/1/17-10/31/17)**	**Estimates of Projected Expenditures (11/1/17-2/28/18)**
1. Vladimir Bulovic - Professor	11,000	-	-
2. Jesus Del Alamo - Professor	5,400	-	-
3. Eugene Fitzgerald - Professor	9,200	19,267	-
4. Jing Kong - Professor	8,250	-	-
5. Jeffrey Lang - Professor	10,900	11,500	-
6. (2) Prof. Swager & new faculty participant TBD	22,800	2,499	-
7. (7)TOTAL SENIOR PERSONNEL (1-6)	**67,550**	**33,266**	**-**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. ( )POST DOCTORAL ASSOCIATES	-	22,588	8,000
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	7,500	34,914	15,000
3. (7)GRADUATE STUDENTS	287,000	127,742	75,000
4. ( )UNDERGRADUATE STUDENTS	-	-	-
5. (1)SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	2,000	6,435	-
6. (1)OTHER	6,000	6,780	6,000
TOTAL SALARIES AND WAGES (A+B)	**370,050**	**231,725**	**104,000**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	30,000	29,310	4,000
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**400,050**	**261,034**	**108,000**
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	5,901	11,599
2. FOREIGN	-		
F. PARTICIPANT SUPPORT COSTS			
1. STIPENDS	24,000	-	24,000
2. TRAVEL	-		-
3. SUBSISTENCE	10,000	-	10,000
4. OTHER	7,750	-	7,750
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS	**41,750**	**-**	**41,750**
G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES	35,000	29,197	6,000
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	3,320	-	2,000
3. CONSULTANT SERVICES	-	-	-
4. COMPUTER SERVICES	9,000	3,398	5,765
5. SUBAWARDS	-	-	-
6. OTHER	270,000	115,000	86,000
TOTAL OTHER DIRECT COSTS	**317,320**	**147,596**	**99,765**
H. TOTAL DIRECT COSTS (A THROUGH G)	**776,620**	**414,532**	**261,114**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	585,000	228,575	200,000
RATE:	56.00%		
TOTAL INDIRECT COSTS (F&A)	**327,600**	**228,575**	**200,000**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**1,104,220**	**643,106**	**461,114**
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**	**643,106**	**461,114**
M. COST SHARING: PROPOSED LEVEL $ -			

Center for Energy Efficient Electronics Science

ORGANIZATION **Stanford University**			
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **H.-S. Philip Wong**			
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 (3/1/17-2/28/18)**	**Actual Expenditure (3/1/17-10/31/17)**	**Estimates of Projected Expenditures (11/1/17-2/28/18)**
1. H.-S. Philip Wong - Professor	17,870	22,159	
2.	-		
3.	-		
4.	-		
5.	-		
6. (1) OTHERS (Sr. Research Scientist)	5,465	3,109	
7. (1)TOTAL SENIOR PERSONNEL (1-6)	**23,335**	**25,268**	-
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. (1)POST DOCTORAL ASSOCIATES	41,766	25,212	
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	-		
3. (1)GRADUATE STUDENTS	-	6,714	
4. ( )UNDERGRADUATE STUDENTS	-		
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	-		
6. ( )OTHER	-		
TOTAL SALARIES AND WAGES (A+B)	**65,101**	**57,194**	-
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	16,603	13,559	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**81,704**	**70,753**	-
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)	750	-	
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	-	6,509	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	1,000	-	
3. CONSULTANT SERVICES	-		
4. COMPUTER SERVICES	-		
5. SUBAWARDS	-		
6. OTHER SU NanoFabrication Faculty user fees	7,629	13,821	
TOTAL OTHER DIRECT COSTS	**8,629**	**20,330**	-
H. TOTAL DIRECT COSTS (A THROUGH G)	**91,083**	**91,083**	-
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	91,083	91,083	
RATE:	57.00%	57.00%	
TOTAL INDIRECT COSTS (F&A)	**51,917**	**51,917**	-
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**143,000**	**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**	**143,000**	-
M. COST SHARING: PROPOSED LEVEL $ -			

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 (3/1/17-2/28/18)**	**Actual Expenditure (3/1/17-10/31/17)**	**Estimates of Projected Expenditures (11/1/17-2/28/18)**
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	50,399	30,650	21,400
4. ( )UNDERGRADUATE STUDENTS	-		
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	-		
6. ( )OTHER	-		
TOTAL SALARIES AND WAGES (A+B)	**63,455**	**43,706**	**21,400**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	11,619	3,090	4,000
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**75,074**	**46,795**	**25,400**
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)	12,600	2,323	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	4,028	10,128	7,055
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	-		
3. CONSULTANT SERVICES	-		
4. COMPUTER SERVICES	-		
5. SUBAWARDS	-		
6. OTHER	3,000		1,000
TOTAL OTHER DIRECT COSTS	**7,028**	**10,128**	**8,055**
H. TOTAL DIRECT COSTS (A THROUGH G)	**94,702**	**59,247**	**35,455**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	94,702	59,246	35,455
RATE:	51.00%	51.00%	51.00%
TOTAL INDIRECT COSTS (F&A)	**48,298**	**30,216**	**18,082**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**143,000**	**89,463**	**53,537**
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**	**89,463**	**53,537**
M. COST SHARING: PROPOSED LEVEL $ -			

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 (3/1/17-2/28/18)**	**Actual Expenditure (3/1/17-10/31/17)**	**Estimates of Projected Expenditures (11/1/17-2/28/18)**
1. Sakhrat Khizroev - Professor	9,705	1,515	3,131
2.	-		
3.	-		
4.	-		
5.	-		
6. ( ) OTHERS	-		
7. (1)TOTAL SENIOR PERSONNEL (1-6)	**9,705**	**1,515**	**3,131**
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)			
1. ( )POST DOCTORAL ASSOCIATES	-		
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	-		3,392
3. (2)GRADUATE STUDENTS	48,912	49,415	14,590
4. ( )UNDERGRADUATE STUDENTS	-		
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)	-		
6. ( )OTHER	-		
TOTAL SALARIES AND WAGES (A+B)	**58,617**	**50,930**	**21,113**
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	6,688	3,753	1,987
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)	**65,305**	**54,683**	**23,100**
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	2,434	5,518
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	20,791	3,602	6,844
2. PUBLICATION/DOCUMENTATION/DISSEMINATION	1,000		-
3. CONSULTANT SERVICES	-		
4. COMPUTER SERVICES	-		
5. SUBAWARDS	-		
6. OTHER	9,461	9,119	
TOTAL OTHER DIRECT COSTS	**31,252**	**12,721**	**6,844**
H. TOTAL DIRECT COSTS (A THROUGH G)	**101,557**	**69,838**	**35,462**
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:	92,096	60,719	**35,462**
RATE:	45.00%	45%	45%
TOTAL INDIRECT COSTS (F&A)	**41,443**	**27,324**	**15,958**
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)	**143,000**	**97,162**	**51,420**
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**	**97,162**	**51,420**
M. COST SHARING: PROPOSED LEVEL $ -			

Center for Energy Efficient Electronics Science

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.

<u>University of California, Berkeley</u>

Unobligated funds from the current award year are estimated to be $1.6M. These unobligated funds are projected to be spent by the end of period 9 for additional support for postdoctoral researchers and graduate student researchers, research materials and supplies, and education and outreach programs. In this regard, we plan to continue and increase the new 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 additional participants in the Education and Diversity program in summer 2017.

<u>Massachusetts Institute of Technology</u>

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

<u>Stanford University</u>

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

<u>The University of Texas at El Paso</u>

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

<u>Florida International University</u>

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	PROPOSAL NO.	DURATION (MONTHS)	
University of California, Berkeley		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		1.50	1.50	$81,113	$
2. Jeff Bokor - Co-PI / Deputy Dir / Res Lead			1.00	$23,286	
3. Tsu-Jae King Liu - Research Lead / AD Educ			1.00	$23,141	
4. Ming Wu - Research Lead			0.50	$12,020	
5. Steve Louie - Faculty Member			0.50	$13,214	
6. (8) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	24		4.00	$303,968	
7. (13) TOTAL SENIOR PERSONNEL (1-6)	24	1.50	8.50	$456,742	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (7) POSTDOCTORAL ASSOCIATES	84			$408,565	
2. (1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.22			$1,500	
3. (7) GRADUATE STUDENTS				$289,262	
4. (1) UNDERGRADUATE STUDENTS				$13,781	
5. (1) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				$61,800	
6. (1) OTHER				$72,200	
TOTAL SALARIES AND WAGES (A + B)				$1,303,849	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$494,364	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$1,798,213	
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)				$66,475	
2. FOREIGN				$18,000	
F. PARTICIPANT SUPPORT 1. STIPENDS $ 74,900 2. TRAVEL $ 16,160 3. SUBSISTENCE $ 32,925 4. OTHER $ 22,762					
TOTAL NUMBER OF PARTICIPANTS (28) TOTAL PARTICIPANT COSTS				$146,747	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$95,430	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				$12,500	
3. CONSULTANT SERVICES				$20,000	
4. COMPUTER SERVICES				$33,391	
5. SUBAWARDS				$1,490,220	
6. OTHER				$166,482	
TOTAL OTHER DIRECT COSTS				$1,818,023	
H. TOTAL DIRECT COSTS (A THROUGH G)				$3,847,457	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) TOTAL INDIRECT COSTS (F&A) Base - Modified Total Direct Costs ($2,022,004) Indirect Rate - 57%				$1,152,543	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$5,000,000	
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)				$5,000,000	$

M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT: $		
PI/PD TYPED NAME AND SIGNATURE* Eli Yablonovitch	DATE 11/27/2017	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION	
ORG. REP. TYPED NAME & SIGNATURE* Joyce So Contract & Grant Officer Digitally signed by Joyce So Date: 2017.11.29 08:39:37 -08'00'	DATE	Date Checked	Date of Rate Sheet / Initials-ORG

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

				FOR NSF USE ONLY		
SUMMARY PROPOSAL BUDGET						
ORGANIZATION **Massachusetts Institute of Technology**				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			50%	11,000	
2. Jesus del Alamo - Professor			25%	5,400	
3. Eugene Fitzgerald - Professor			50%	9,200	
4. Jing Kong - Professor			50%	8,250	
5. Jeff Lang - Professor			50%	10,900	
6. (2) Prof. Swager & new faculty participant TBD			100%	22,800	
7. ( )TOTAL SENIOR PERSONNEL (1-6)			3.25	**67,550**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( )POST DOCTORAL ASSOCIATES					
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)				7,500	
3. (7)GRADUATE STUDENTS				287,000	
4. ( )UNDERGRADUATE STUDENTS					
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)				2,000	
6. ( )OTHER				6,000	
TOTAL SALARIES AND WAGES (A+B)				**370,050**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				30,000	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**400,050**	
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	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS	24,000				
2. TRAVEL					
3. SUBSISTENCE	10,000				
4. OTHER	7,750				
TOTAL NUMBER OF PARTICIPANTS ( )	TOTAL PARTICIPANT COSTS			**41,750**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				35,000	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				3,320	
3. CONSULTANT SERVICES				-	
4. COMPUTER SERVICES				9,000	
5. SUBAWARDS				-	
6. OTHER				270,000	
TOTAL OTHER DIRECT COSTS				**317,320**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**776,620**	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE)	MTDC BASE:		585,000		
TOTAL INDIRECT COSTS (F&A)	RATE:		56.00%	**327,600**	
J. TOTAL DIRECT AND INDIRECTS COSTS (H + I)				**1,104,220**	
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**	
M. COST SHARING: PROPOSED LEVEL $		AGREED LEVEL IF DIFFERENT $			

PI/PD TYPED NAME & SIGNATURE* Vladimir Bulovic [signature]	DATE 11/27/2017	FOR NSF USE ONLY		
		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Michael Leskiw [signature]	DATE 11/27/2017	Date Checked	Date of Rate Sheet	Initials - ORG

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SUMMARY PROPOSAL BUDGET

ORGANIZATION **Stanford University**				FOR NSF USE ONLY		
				PROPOSAL NO.	DURATION (MONTHS)	
					Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **H.-S. Philip Wong**				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			Funds Requested By Proposer	Funds Granted by NSF (If Different)	
	CAL	ACAD	SUMR			
1. H.-S. Philip Wong - Professor			0.45	11,212		
2.						
3.						
4.						
5.						
6. ( ) OTHERS						
7. (1)TOTAL SENIOR PERSONNEL (1-6)			0.45	**11,212**		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( )POST DOCTORAL ASSOCIATES						
2. (1)OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)	0.6			9,427		
3. (1)GRADUATE STUDENTS				31,751		
4. ( )UNDERGRADUATE STUDENTS						
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)						
6. ( )OTHER (Tuition)				20,807		
TOTAL SALARIES AND WAGES (A+B)				**73,197**		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				7,759		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**80,956**		
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				2,000		
2. PUBLICATION/DOCUMENTATION/DISSEMINATION						
3. CONSULTANT SERVICES						
4. COMPUTER SERVICES						
5. SUBAWARDS						
6. OTHER (Nano Fabrication facility use fees)				13,681		
TOTAL OTHER DIRECT COSTS				**15,681**		
H. TOTAL DIRECT COSTS (A THROUGH G)				**98,637**		
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE)						
MTDC BASE:			77,830			
TOTAL INDIRECT COSTS (F&A) RATE:			57.00%	**44,363**		
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*	DATE 11/10/17		FOR NSF USE ONLY			
			INDIRECT COST RATE VERIFICATION			
ORG. REP. TYPED NAME & SIGNATURE*	DATE 11/15/17		Date Checked	Date of Rate Sheet	Initials - ORG	

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Center for Energy Efficient Electronics Science

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			Funds Requested By Proposer	Funds Granted by NSF (If Different)	
	CAL	ACAD	SUMR			
1. David Zubia - Professor			1.00	13,056		
2.						
3.						
4.						
5.						
6. ( ) OTHERS						
7. (1)TOTAL SENIOR PERSONNEL (1-6)			1	13,056		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( )POST DOCTORAL ASSOCIATES						
2. ( )OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)						
3. ( )GRADUATE STUDENTS				46,500		
4. ( )UNDERGRADUATE STUDENTS						
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)						
6. ( )OTHER						
TOTAL SALARIES AND WAGES (A+B)				59,556		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				8,585		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				68,141		
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				20,561		
2. PUBLICATION/DOCUMENTATION/DISSEMINATION						
3. CONSULTANT SERVICES						
4. COMPUTER SERVICES						
5. SUBAWARDS						
6. OTHER						
TOTAL OTHER DIRECT COSTS				20,561		
H. TOTAL DIRECT COSTS (A THROUGH G)				94,702		
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE)						
MTDC BASE:			94,702			
TOTAL INDIRECT COSTS (F&A) RATE:			51.00%	48,298		
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*	DATE 11/16/2017	FOR NSF USE ONLY				
		INDIRECT COST RATE VERIFICATION				
ORG. REP. TYPED NAME & SIGNATURE* Raul Chavez	DATE 11/16/2017	Date Checked	Date of Rate Sheet	Initials - ORG		

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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 Khizroev		0.54		10,811	
2.					
3.					
4.					
5.					
6. ( ) OTHERS					
7. (1)TOTAL SENIOR PERSONNEL (1-6)		0.54		10,811	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( )POST DOCTORAL ASSOCIATES					
2. (1)OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC)				5,000	
3. (1)GRADUATE STUDENTS				27,600	
4. ( )UNDERGRADUATE STUDENTS					
5. ( )SECRETARIAL-CLERICAL (IF CHARGED DIRECTLY)					
6. ( )OTHER					
TOTAL SALARIES AND WAGES (A+B)				43,411	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,341	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				48,753	
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	
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. PUBLICATION/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER (printing & reproduction) & Tuition				11,175	
TOTAL OTHER DIRECT COSTS				18,184	
H. TOTAL DIRECT COSTS (A THROUGH G)				71,937	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) MTDC BASE:		62,363			
TOTAL INDIRECT COSTS (F&A) RATE:		45.00%		28,063	
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* Sakhrat Khizroev	DATE 11/21/17	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION
ORG. REP. TYPED NAME & SIGNATURE*	DATE 11/22/17	Date Checked / Date of Rate Sheet / Initials - ORG

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*SIGNATURE REQUIRED ONLY FOR REVISED BUDGET(GPG III.C

Roberto M. Gutierrez
Assistant Vice President for Research
Office of Research and Economic Development

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	171,678	69,000[1]	119,924	
Other Federal Agencies		34,000[2]		
State Government				
Local Government				
Industry	162,500			
University	106,950	30,350[3]	40,000	2,600
International		40,452[4]		
Private Foundations				
Other				
TOTAL	**5,441,128**	**173,802**	**5,159,924**	**2,600**

[1]NSF Graduate Research Fellowships
[2]NSDEG Graduate Fellowship
[3]UC Berkeley Chancellor Fellowship; UC Berkeley TTE-REU Tuition Waiver; UTEP Murchison Graduate Fellowship
[4]CEA Stipend to ETERN; SOIC Postdoc Fellowship from China; 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	121,704	23,000[1]	119,924	
NSF Office of Integrative Activities	49,974			
NSF Directorate for Mathematical & Physical Sciences		46,000[1]		
TOTAL	**171,678**	**69,000**[1]	**119,924**	

[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 ____________ Date: 11/19/2015

Title: Award Analyst

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	1,952,960	-	1,284,395	-
Other Federal Agencies	7,003,772	-	3,000,433	-
State Government	697,090	-	697,090	-
Local Government	-	-	-	-
Industry	1,744,426	-	969,405	-
University	565,722	9,167	1,818,144	9,333
International	6,151,944	-	5,000,000	-
Private Foundations	75,000	-	575,000	-
Other	-	-	-	-
TOTAL	**18,190,914**	**9,167**	**13,344,467**	**9,333**

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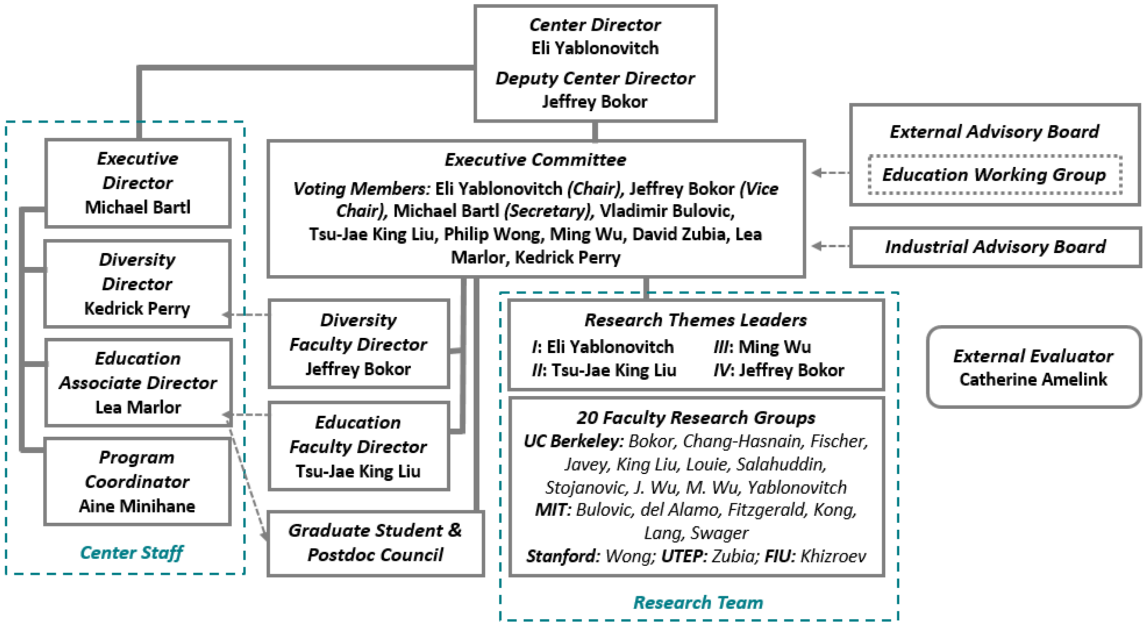
XII. APPENDICES

Appendix A: Organizational Chart



Appendix B: External Advisory Board Meeting Agenda

Center for Energy Efficient Electronics Science
2017 External Advisory Board Meeting

October 18, 2017
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, Farnaz Niroui**
	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, Charles-Henri Lambert**
	0:15	Q&A	
3:10 PM		**System Integration**	
	0:20	Research Presentation	**Vladimir Stojanović**
	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^3S and Dinner**	

2016 EAB Meeting Advance Agenda

Center for Energy Efficient Electronics Science

Appendix C: 2017 Research Seminar Attendance

Dates	Faculty	Postdocs	Graduate Students	Undergrad Students	Staff	Other
	2017 Seminar Series					
February 23	0	10	9	0	4	3
March 3	2	7	8	0	5	2
March 23	1	9	3	2	2	2
April 6	3	12	5	0	5	0
April 13	3	8	7	0	4	1
June 15	2	6	16	16	4	2
June 22	2	3	4	17	4	1
July 20	1	1	7	16	3	3
July 27	3	3	7	17	4	1
October 4	2	2	9	0	6	1
November 9	3	3	9	0	6	0
November 16	1	5	4	0	5	0

Appendix D: E^3S Professional Development Program

Objective: Equip E^3S 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

<u>Leadership*</u>

- 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^3S representative, theme meeting coordinator, REU selection committee, poster session evaluator

<u>Teaching*</u>

- 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^3S summer school, online course development, MOSTEC instructor

<u>Mentoring*</u>

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

<u>Outreach</u>

- 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

<u>Science Communication</u>

- 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^3S Symposium; presentation at annual retreat, EAB, Site Visit, Journal Club, Research seminar, or E^3S Symposium

Proposal Writing

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

2017 Joint Recruitment Calendar

for Summer Research Experiences for Undergraduates and Engineering Graduate Diversity

September 2017			
AISES	September 21	Denvoer, CO	E3S
October 2017			
Atlanta Consortium and Clark Altanta	October 10	Altanta, CA	E3S
NOBCChe	October 30	Minneapolis, MN	E3S
Howard Grad Fair	October 31	Washington DC	E3S
November 2017			
Society of Hispanic Professional Engineers (SHPE)	November 3	Kansas City, MO	
OSTEM	November 16-19	Chicago, IL	E3S
NC A&T	November 20	Greensboro, NC	E3S

Appendix F: TTE REU Recruitment Calendar

Santa Barbara City College	September 25	Santa Barbara, CA
Allan Hancock College	September 26	Santa Maria, CA
Ventura College	September 26	Ventura, CA
San Diego City College	September 27	San Diego, CA
Southwestern College	September 27	Chula Vista, CA
El Camino College	September 28	Torrance, CA
Santa Ana College	September 28	Santa Ana, CA
LA Trade Technical College	September 29	Los Angeles, CA
TTE Webinars	October 25 and November 14	Online

Appendix G: 2017 Fifth Berkeley Symposium on Energy Efficient Electronic Systems

5th Berkeley Symposium on Energy Efficient Electronic Systems & Steep Transistors Workshop

University of California, Berkeley, Sutardja Dai Hall, 3rd Floor, Banatao Auditorium

THURSDAY, OCTOBER 19, 2017

8:30 am **REGISTRATON & BREAKFAST**

9:15 am ***Welcome Remarks***

Eli Yablonovitch & Jeffrey Bokor (University of California, Berkeley, USA)

9:30 am ***Systems Benefits of Lower Operating Voltage***
Chairs: Jeffrey Bokor, Eli Yablonovitch, University of California, Berkeley, USA

9:30 am **Paolo Gargini** (IRDS, USA) *invited*
"Roadmap Evolution: From NTRS to ITRS, from ITRS 2.0 to IRDS"

9:50 am Questions & Discussion

9:55 am **Adrian Ionescu** (Ecole Polytechnique Fédérale Lausanne, Switzerland) *invited*
"Sub-unity Body Factor: The Next CMOS and Beyond CMOS Technology Booster for Enhanced Energy Efficiency?"

10:15 am Questions & Discussion

10:20 am **Subhasish Mitra** (Stanford University, USA) *invited*
"N3XT 3D Nanosystems for Energy-Efficient Abundant-Data Computing"

10:40 am Questions & Discussion

10:45 am **Takahiro Hanyu** (Tohoku University, Japan) *invited*
"Standby-Power-Free Integrated Circuits Using MTJ-Based VLSI Computing for IoT Applications"

11:05 am Questions & Discussion

11:10 am **BREAK**

11:25 am ***Analog and Digital Accelerators for Deep Learning***
Chair: Eli Yablonovitch, University of California, Berkeley

11:25 am **Amir Khosrowshahi** (Intel Corporation, USA) *invited keynote*
Keynote Presentation: "Building a Platform for AI"

12:00 am Questions & Discussion

12:05 am **Engin Ipek** (University of Rochester, USA) and Mahdi Nazm Bojnordi (University of Utah, USA) *invited*
"Memristive Boltzmann Machine: A Hardware Accelerator for Combinatorial Optimization and Deep Learning"

12:25 pm Questions & Discussion

12:30 pm **LUNCH**

1:30 pm ***Steep Tunnel Transistors for Reduced Operating Voltage***
Chair: Lars-Erik Wernersson, Lund University

1:30 pm **Alan Seabaugh** (University of Notre Dame, USA) *invited*
"Advance of Steep Transistors"

1:50 pm Questions & Discussion

1:55 pm **Shinichi Takagi**, Daehwan Ahn, Takahiro Gotow, Koichi Nishi, Taeeon Bae, Takumi Katoh, Ryo Matsumura, Ryotaro Takaguchi, Kimihiko Kato and Mitsuru Takenaka (University of Tokyo, Japan) *invited*
"III-V/Ge-based Tunneling MOSFET"

2:15 pm Questions & Discussion

2:20 pm **Ru Huang**, Qianqian Huang, Yang Zhao, Cheng Chen, Rundong Jia, Lingyi Guo and Yangyuan Wang (Peking University, China) *invited*
"Steep Switch with Hybrid Operation Mechanism for Performance Improvement"

2:40 pm Questions & Discussion

2:45 pm **Peter Asbeck** and Jie Ming (University of California, San Diego, USA)
"Modeling the Influence of Dielectric Interface Traps on I-V Characteristics of TFETs"

3:00 pm Questions & Discussion

3:05 pm **BREAK**

3:20 pm ***Strategies for Neuromorphic Computing***
Chair: Jeffrey Bokor, University of California, Berkeley

3:20 pm **Yichen Shen**, Nicholas C. Harris, Dirk Englund and Marin Soljacic (Massachusetts Institute of Technology, USA) *invited*
"Deep Learning with Coherent Nanophotonic Circuits"

3:40 pm Questions & Discussion

3:45 pm **Shunsuke Fukami**, William Borders, Aleksandr Kurenkov, Chaoliang Zhang, Samik Duttagupta and Hideo Ohno (Tohoku University, Japan) *invited*
"Use of Analog Spintronics Device in Performing Neuro-morphic Computing Functions"

4:05 pm Questions & Discussion

4:10 pm **Sapan Agarwal**, Alexander Hsia, Robin Jacobs-Gedrim, David R. Hughart, Steven J. Plimpton, Conrad D. James and Matthew Marinella (Sandia National Laboratories, USA) *invited*
"Designing an Analog Crossbar-based Neuromorphic Accelerator"

4:30 pm Questions & Discussion

4:35 pm **Masanao Yamaoka** (Hitachi Ltd., Japan) *invited*
"An Ising Computing to Solve Combinatorial Optimization Problems"

4:55 pm Questions & Discussion

5:00 pm **BREAK**

5:10 pm ***Panel Discussion on Deep Learning and Neural Networks***

Moderator: Jan Rabaey, University of California, Berkeley

Panelists: Amir Khosrowshahi, Engin Ipek, Masanao Yamaoka, Yichen Shen, Shunsuke Fukami, Sapan Agarwal

5:50 pm **WALK TO POSTER SESSION**

6:00 pm ***Poster Session & Reception (for list of posters see below)***

8:00 pm **END OF DAY 1**

FRIDAY, OCTOBER 20

8:45 am **BREAKFAST (& REGISTRATION)**

9:30 am ***Negative Capacitance Transistors***
Chair: Sayeef Salahuddin, University of California, Berkeley

9:30 am **Masaharu Kobayashi** (University of Tokyo, Japan) *invited*
"Technology Breakthrough by Ferroelectric HfO2 for Ultralow Power Logic and Memory"

9:50 am Questions & Discussion

9:55 am **Zoran Krivokapic**, Ahmedullah Aziz, Da Song, Uzma Rana, Rohit Galatage and Srinivasa Banna (GlobalFoundries, USA) *invited*
"NCFET: Opportunities & Challenges for Advanced Technology Nodes"

10:15 am Questions & Discussion

10:20 am **BREAK**

10:30 am ***Ultrafast Magnetic Switching***
Chair: Eli Yablonovitch, University of California, Berkeley

10:30 am **Jeffrey Bokor** (University of California, Berkeley, USA) *invited*
"Prospects for Ultrafast MRAM with <10 psec Write Latency"

10:50 am Questions & Discussion

10:55 am **Lucian Prejbeanu**, Andrey Timopheev, Ricardo Sousa, Gilles Gaudin and Bernard Dieny (SPINTEC, CEA Grenoble, France) *invited*
"Ultrafast MRAM Strategies for Cache Applications and Beyond"

11:15 am Questions & Discussion

11:20 am ***Adaptive Neural Networks***
Chair: Eli Yablonovitch, University of California, Berkeley

11:20 am **Gert Cauwenberghs** (University of California, San Diego, USA) *invited*
"Energy Efficiency in Adaptive Neural Circuits"

11:40 am Questions & Discussion

11:45 am **LUNCH**

12:45 pm ***New Mechanisms for Energy Efficient Computing***

Chair: Nerissa Draeger, Lam Research

12:45 pm **Farnaz Niroui**, Jatin Patil, Timothy Swager, Jeffrey Lang and Vladimir Bulovic (Massachusetts Institute of Technology, USA)
"Towards Low-Stiction Nanoelectromechanical Switches Using Self-Assembled Molecules"

1:00 pm Questions & Discussion

1:05 pm **Vladimir Stojanovic**,[1] Sajjad Moazeni,[1] Amir Atabaki,[2] Fabio Pavanello,[3] Hayk Gevorgyan,[4] Jelena Notaros,[2] Luca Alloatti,[2] Mark Wade,[5] Chen Sun,[5] Seth Kruger,[6] Huaiyu Meng,[2] Kenaish Al Qubaisi,[4] Imbert Wang,[4] Bohan Zhang,[4] Anatol Khilo,[4] Christopher Baicco,[6] Milos Popovic,[4] and Rajeev Ram[2] ([1]University of California, Berkeley, USA, [2]Massachusetts Institute of Technology, USA, [3]Ghent University-IMEC, Belgium, [4]Boston University, USA, [5]Ayar Labs, Inc., USA, [6]SUNY Polytechnic Institute, USA)
"Integration of Polysilicon-based Photonics in a 12-inch Wafer 65nm Bulk CMOS Process"

Questions & Discussion

1:20 pm

1:25 pm **Seth Fortuna**, Christopher Heidelberger, Nicolas Andrade, Kevin Han, Eugene Fitzgerald, Eli Yablonovitch and Ming Wu (University of California, Berkeley and Massachusetts Insitute of Technology, USA)
"Large Spontaneous Emission Rate Enhancement in a Nanoscale III-V LED Coupled to an Optical Antenna"

Questions & Discussion

1:40 pm

1:45 pm BREAK

1:55 pm *Defects and Energy Level Characteristics of Tunnel Transistors*

Chair: Alan Seabaugh, University of Notre Dame

1:55 pm **Jesus del Alamo**, Xin Zhao, Lu Wenjie and Vardi Alon (Massachusetts Institute of Technology, USA) *invited*
"Towards Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs and TFETs"

2:15 pm Questions & Discussion

2:20 pm **Lars-Erik Wernersson** (Lund University, Sweden) *invited*
"III-V Nanowire TFETs: Performance, Statistics, and Band Edge Sharpness"

2:40 pm Questions & Discussion

2:45 pm **Anne Verhulst**,[1] Devin Verreck,[1] William G. Vandenberghe,[2] Quentin Smets,[1] Mazharuddin Mohammed,[1,3] Jasper Bizindavyi,[1,3] Marc M. Heyns,[1,3] Bart Soree,[1,3,4] Nadine Collaert,[1] and Anda Mocuta[1] ([1]IMEC, Leuven, Belgium, [2]Univ. of Texas at Dallas, USA, [3]KU Leuven, Belgium, [4]UAntwerp, Belgium) *invited*
"Inherent Transmission Probability Limit Between Valence-band and Conduction-band States and Calibration of Tunnel-FET Parasitics"

3:05 pm Questions & Discussion

3:10 pm **Felix Fischer** (University of California, Berkeley, USA)
"Graphene Nanoribbon Band Gap Engineering Through Orbitally Matched Dopant Atoms"

3:25 pm Questions & Discussion

3:30 pm **Sheikh Ahmed**, Yaohua Tan, Daniel Truesdell and Avik Ghosh (University of Virginia, USA)
"Auger Effect Limited Performance in Tunnel Field Effect Transistors"

Questions & Discussion

3:45 pm

3:50 pm ***Closing Remarks***

Eli Yablonovitch & Jeffrey Bokor (University of California, Berkeley, USA)

4:00 pm **END OF SYMPOSIUM**

SYMPOSIUM POSTERS

Authors	Poster Title
Jasper Bizindavyi, Anne S. Verhulst, Quentin Smets, Devin Verreck, Nadine Collaert, Anda Mocuta, Bart Sorée and Guido Groeseneken	*Calibration of the high-doping induced ballistic band-tails tunneling current with In0.53Ga0.47As Esaki diodes*
Sarthak Gupta, Kaushal Nigam, Sunil Pandey, Dheeraj Sharma and Pravin Kondekar	*Performance Improvement of Heterojunction Double Gate Drain Overlapped TFET using Gaussian Doping*
Dheeraj Sharma, Bhagwan Ram Raad and Sukeshni Tirkey	*Channel Engineered Tunnel FET for Reduced Ambipolar Nature*
Jon Gorchon, Charles-Henri Lambert, Yang Yang, Akshay Pattabi, Sayeef Salahuddin and Jeffrey Bokor	*Single shot ultrafast all optical magnetization switching of ferromagnetic Co/Pt multilayers*
Stefan Glass, Christian Schulte-Braucks, Lidia Kibkalo, Uwe Breuer, Jean-Michel Hartmann, Dan Buca, Siegfried Mantl and Qing-Tai Zhao	*Examination of a new SiGe/Si heterostructure TFET concept based on vertical tunneling*
Rebecca Durr, Danny Haberer, Yea-Lee Lee, Alin Miksi Kalayjian, Raymond Blackwell, Tomas Marangoni, Steven Louie and Felix Fischer	*Graphene Nanoribbon Band Gap Engineering Through Orbitally Matched Dopant Atoms.*
Zhifu Liu, Peter Girouard, Pice Chen, Young Kyu Jeong, Seng-Tiong Ho and Bruce W. Wessels	*50 GHz Electro-optic Modulators with BaTiO3 Epitaxial Thin Film Platform for Short Distance Optical Communications*
Francesco Settino, Sebastiano Strangio, Marco Lanuzza, Felice Crupi, Pierpaolo Palestri and David Esseni	*Simulations and comparisons of basic analog and digital circuit blocks employing Tunnel FETs and conventional FinFETs*
Yasmine Elogail, Joerg Schulze and Inga Fischer	*Fabrication and Simulation of Vertical Ge-based P-Channel Planar-Doped Barrier FETs with 40 nm Channel Length*
Shaloo Rakheja and Kexin Li	*Graphene-Based Plasma Wave Interconnects for On-Chip Communication in the Terahertz Band*
Jun Huang, Pengyu Long, Michael Povolotskyi, Gerhard Klimeck and Mark Rodwell	*Sb- and Al- Free Ultra-High-Current Tunnel FET Designs*
Hongjuan Wang, Xiangwei Jiang, Genquan Han, Yue Hao, Shushen Li and David Esseni	*Revisiting Piezoelectric FETs with Sub-Thermal Swing*

Pin-Chun Shen and Jing Kong	*Chemical Vapor Deposition of High-Quality Monolayer Transition Metal Disulfides*
Sajjad Moazeni, Amir Atabaki, Fabio Pavanello, Hayk Gevorgyan, Jelena Notaros, Luca Alloatti, Mark Wade, Chen Sun, Seth Kruger, Huaiyu Meng, Kenaish Al Qubaisi, Imbert Wang, Bohan Zhang, Anatol Khilo, Christopher Baicco, Milos Popovic, Rajeev Ram and Vladimir Stojanovic	*Integration of Polysilicon-based Photonics in a 12-inch Wafer 65nm Bulk CMOS Process*
Bivas Saha, Benjamin Osoba, Tsu Jae King Liu and Junqiao Wu	*Materials Engineering of Micro-relay Contact Surfaces for milli-Volt Switching*
Sri Krishna Vadlamani and Eli Yablonovitch	*On the broadening of energy levels in a quantum dot-based tunnel transistor*
Nishtha Sharma, Andrew Marshall, Jonathan Bird and Peter Dowben	*Verilog-A based Compact Modeling of the Magneto-electric FET Device*
Nishtha Sharma, Andrew Marshall, Jonathan Bird and Peter Dowben	*Novel Ring Oscillator Design Using ME-MTJ Based Devices*
William Vandenberghe	*Two-dimensional Topological Insulator Transistors as Energy Efficient Switches Robust against Material and Device Imperfections*
Ting Cao, Fangzhou Zhao, Yea-Lee Lee and Steven G. Louie	*Graphene Nanoribbons for Transistor Applications*
Taeeon Bae, Ryota Suzuki, Ryosho Nakane, Mitsuru Takenaka and Shinichi Takagi	*Effects of Ge-source impurity concentration on electrical characteristics of Ge/Si hetero-junction tunneling FETs*
Jean Anne Incorvia, Elyse Barre, Suk Hyun Kim, Connor McClellan, Eric Pop, H.-S. Philip Wong and Tony Heinz	*Near-room temperature electrical control of spin and valley Hall effect in monolayer WSe2 transistors for spintronic applications*
Sean Hooten and Eli Yablonovitch	*Metallodielectric Antenna for Spontaneous Emission Enhancement*
Sergio Almeida, David Zubia, Aldo Vidaña and Mariana Martinez	*Conductance Modulation in 2D Materials by NEMS for Lower-Power Applications*
Amal El-Ghazaly, Daisy O'Mahoney, Charles-Henri Lambert, Jon Gorchon, P. Nigel Brown, Akshay Pattabi, H.S. Philip Wong and Jeffrey Bokor	*Ultrafast Magnetic Memory Bits Using All-Optical Magnetic Switching*
Nicolas Andrade, Seth Fortuna, Kevin Han, Sean Hooten, Eli Yablonovitch and Ming Wu	*Efficient and Broadband Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based nanoLED*
Brayan Navarrete, Mark Stone and Sakhrat Khizroev	*Properties of Magnetic Tunneling Junction Devices with Characteristic Sizes in Sub-5-nm Range*
Samuel Xavier-De-Souza, Eduardo Neves, Alex Furtunato, Luiz Silveira, Kyriakos Georgiou and Kerstin Eder	*The Benefits of Low Operating Voltage Devices to the Energy Efficiency of Parallel Systems*
Peida Zhao, Matin Amani, Der-Hsien Lien, Geun Ho Ahn, Daisuke Kiriya, James P. Mastandrea, Joel W. Ager, Eli Yablonovitch, Daryl C. Chrzan and	*Measuring the Edge Recombination Velocity of Monolayer Semiconductors*

Ali Javey	
Mirza M. Elahi, K. M. Masum Habib and Avik W. Ghosh	*Gate tunable transport-gap to beat the Boltzmann limit: a Graphene Klein Tunnel Field Effect Transistor*
Zhixin Alice Ye, Hei Kam and Tsu-Jae King Liu	*Negative Stiffness Structures for Energy Efficient MEM Switches*
Matin Amani, Der-Hsien Lien, Daisuke Kiriya, Geun Ho Ahn, Peida Zhao, Joel Ager, Eli Yablonovitch and Ali Javey	*High Photoluminescence Quantum Yield in Transition Metal Dichalcogenides Enabled by Superacid Treatment*
Sreetosh Goswami and T. Venkatesan	*Resistive Memory Devices using Metal-Coordinated Azo-aromatics*

Appendix H: 2017 HBCU Workshop

2017 UCB-HBCU Faculty Workshop

Sutardja Dai Hall Rm 242

Time	Duration	Topic	Speaker/Host
Tuesday, April 4, 2017			
5:30PM	1:30	Dinner (Skates on the Bay, 100 Seawall Drive Berkeley)	T.-J. King Liu & K. Perry
Wednesday, April 5, 2017			
8:00AM	0:20	Bus to Campus from LBL Guest House	
8:20AM	0:25	Arrival and Breakfast	
8:45AM	0:10	Introduction, Review of Agenda, & Meeting Goals	Tsu-Jae King Liu
8:55AM	0:20	Introduction to the Center for E^3S	Michael Bartl
9:15AM	1:00	*Overview of UC Berkeley, College of Engineering, and the EECS Department *Review of the UCB-HBCU Program *EE undergrad academic preparation at UC Berkeley	Tsu-Jae King Liu
10:15AM	0:05	Break	
10:20AM	0:30	Mini- tour of UC Berkeley	Perez Lowery
10:50AM	0:45	Introduction to Virginia State University Research in the Subramanian Group	Peng Cheng Raj Kumar
11:35AM	1:25	Lunch with BGESS at the Faculty Club	B. Osoba & C. Biaou
1:00PM	0:45	Introduction to Norfolk State University Research in the Bokor Group	Demetris Geddis Jeffrey Bokor
1:45PM	0:05	Break	
1:50PM	0:45	Introduction to University of Maryland Eastern Shore Research in the Yablonovitch Group	Lei Zhang Eli Yablonovitch
2:35PM	0:10	Break	
2:45PM	0:45	Introduction to Prairie View A&M Research in the Arias Group	Paul Potier Karthik Gopalan
3:30PM	0:45	Introduction to Hampton University Research in the King Liu Group	Michelle Claville Benjamin Osoba
4:15PM	0:10	Break	
4:25PM	0:35	Graduate Admissions at Berkeley	Tiffany Reardon

5:00PM	0:30	Travel to Dinner	
5:30PM	1:30	Dinner (Agrodolce, 1730 Shattuck Ave, Berkeley)	
7:00PM		End of Day 1	
		Thursday, April 6, 2017	
8:00AM	0:15	Bus to Campus from LBL Guest House	
8:15AM	0:15	Arrival and Breakfast	
8:30AM	0:30	Summer Internship Program: Expectations, Programming	Lea Marlor
9:00AM	0:15	Break	
9:15AM	2:00	Lab Tours: Marvel NanoLab, Device Characterization Lab, etc	

Appendix I: 2017 E^{3}S Annual Retreat Agenda

8th Annual Retreat
Center for Energy Efficient Electronics Science

September 7-8, 2017
RLE Building 36
MIT Campus

ADVANCE AGENDA

Day 1 – Thursday, September 7, 2017

RLE Building 36, Allen & Haus Rooms (36-428)

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 III-V Nanowire Transistor Project	**Jesús del Alamo**
	Progress on 2D Chalcogenide Transistor Project	**Ali Javey**
	Progress on Graphene Nanoribbon Project	**Eli Yablonovitch**
	Open Discussion	
9:45 AM	***Break***	
10:00 AM	**Theme II: Nanomechanics**	
	Theme II Overview	**Tsu-Jae King Liu**
	Progress on NEM Relay Project	**Bivas Saha**
	Progress on Squitch Project	**Farnaz Niroui**
	Progress on Stritch Project	**David Zubia**
	Open Discussion	
11:15 AM	**Keynote Presentation**	
	Large-Scale Photonic Integrated Circuits for Quantum Information Science and Machine Learning	**Dirk Englund**
12:00 PM	***Lunch***	

2017 Retreat Advance Agenda Day 1

Center for Energy Efficient Electronics Science

1:00 PM	**Theme III: Nanophotonics**	
	Theme III Overview	**Ming Wu**
	Progress on III-V Epitaxial Growth	**Eugene Fitzgerald**
	Progress on Antenna-Enhanced LEDs	**Seth Fortuna**
	Open Discussion	
2:15 PM	***Break***	
2:25 PM	**Theme IV: Nanomagnetics**	
	Theme IV Overview and Ultrafast Magnetic Switching	**Jeffrey Bokor**
	Spin-Orbit Torque Switching Project	**Charles-Henri Lambert**
	CMOS Integration Project	**Jean-Anne Incorvia**
	Open Discussion	
3:40 PM	**Knowledge Transfer**	**Michael Bartl**
3:50 PM	***Break***	
4:00 PM	**Meeting with Industry Partners**	
4:45 PM	***Walk to Poster Session & Dinner***	
5:15 PM	**Reception and Poster Session**	
	Café ArtScience, 650 East Kendall St., Cambridge (www.cafeartscience.com)	
6:30 PM	**Dinner and Recognitions**	
	Café ArtScience, 650 East Kendall St., Cambridge (www.cafeartscience.com)	

8th Annual Retreat

Center for Energy Efficient Electronics Science

September 7-8, 2017
RLE Building 36
MIT Campus

ADVANCE AGENDA

Day 2 – Friday, September 8, 2017

RLE Building 36, Allen & Haus Rooms (36-428)

Time	Activity / Topic	Speaker / Facilitator
7:30 AM	***Breakfast***	
8:00 AM	**System Integration**	
	System Integration Overview	**Vladimir Stojanović**
	Open Discussion	
8:30 AM	**Elevator Pitches**	
	90-Seconds Research Presentations	**E3S Students & Postdocs**
	Feedback & Discussion	Moderators: **Lea Marlor, Kedrick Perry**
10:00 AM	***Break***	
10:15 AM	**Education and Diversity**	
	Inclusion and Diversity Overview	**Kedrick Perry**
	Education Overview	**Lea Marlor**
	Open Discussion	
11:15 AM	**Center Management**	**Michael Bartl**
11:30 AM	**A Look Beyond 2020: Center Legacy**	
	Open Discussion	Moderator: **Vladimir Bulović**
11:55 AM	**Closing Remarks**	**Eli Yablonovitch**
12:00 PM	***Lunch (boxed)***	

2017 Retreat Advance Agenda Day 2

Center for Energy Efficient Electronics Science

Appendix J: 2017 Annual Retreat Poster List

Authors	Poster Title
Design Optimization for NEM Logic Relays in CMOS BEOL Process	Urmita Sikder and Tsu-Jae King Liu
TMDC Based nanoLEDs for High-Speed Energy-Efficient Optical Interconnects	Kevin Han, Seth Fortuna, Matin Amani, Sujay Desai, Eli Yablonovitch, Ali Javey, and Ming C. Wu
Efficient and Broadband Single-Mode Waveguide Coupling of Electrically Injected Optical Antenna Based nanoLED	Nicolás M. Andrade, Seth A. Fortuna, Kevin Han, Sean Hooten, Eli Yablonovitch, and Ming C. Wu
Materials Engineering of Micro-relay Contact Surfaces for milli-Volt Switching	Bivas Saha, Benjamin Osoba, Tsu-Jae King Liu and Junqiao Wu
CVD Growth of High CVD Growth of High - Quality Monolayer	Pin-Chun Shen and Jing Kong
Negative Stiffness Structures for Energy Efficient MEM Switches	Zhixin Alice Ye, Hei Kam, Tsu-Jae King Liu
Synthesizing and Utilizing Atomically Defined Graphene Nanostructures	Rebecca A. Durr, Danny Haberer, Tomas Marangoni, Raymond E. Blackwell Alin M. Kalayjian, and Felix R. Fischer
Designing Graphene Nanoribbon Transistors for Future Electronics	Fangzhou Zhao, Ting Cao, Yea-Lee Lee, and Steven G. Louie
Ultrafast Magnetic Memory Bits Using All-Optical Magnetic Switching	Amal El-Ghazaly , Daisy O'Mahoney , Charles-Henri Lambert , Jon Gorchon, P. Nigel Brown, Akshay Pattabi, H.S. Philip Wong, and Jeffrey Bokor
Single shot ultrafast all optical magnetization switching of ferromagnets	A. Pattabi, J. Gorchon, C.-H. Lambert, Y. Yang, R. Wilson, S. Salahuddin, and J. Bokor
Electrically-injected antenna-LED for on-chip optical communication	Seth A. Fortuna, Christopher Heidelberger, Nicolas Andrade, Kevin Han, Eugene A. Fitzgerald, Eli Yablonovitch, and Ming C. Wu
Metallo -Dielectric Antenna for Spontaneous Emission Enhancement	Sean Hooten, Seth Fortuna, Nicolas Andrade, Kevin Han, Ming Wu, and Eli Yablonovitch
Simulated Novel Comb-Drive MEMS Actuators Intended for Mechanical Strain of 2D-Layered MoS2	Mariana Martinez, Aldo Vidaña, David Zubia, Sergio Almeida, and Jose Mireles

Measuring the Edge Recombination Velocity of Monolayer Semiconductors	PeidaZhao, MatinAmani, Der-Hsien Lien, GeunHo Ahn, Daisuke Kiriya, James P. Mastandrea, Joel W. Ager III, Eli Yablonovitch, Daryl C. Chrzan, and Ali Javey
Increasing “On/Off” Ratio in Sub -5-nm Magnetic nm Magnetic Devices	Brayan Navarrete, Mark Stone , , Ali Hadjikhani , Ali Hadjikhani , Ali Hadjikhani, Kevin Luongo, Ping Wang, Vladimir Safonov, Jeongmin Hong, Jeffrey Bokor, and Sakhrat Khizroev
Ultrafast Magnetization Reversal by Electrical Pulses	C.H. Lambert1 , Y. Yang1 , R.B. Wilson2 , J. Gorchon1, J. Bokor1 and S. Salahuddin1
Process Induced Variation Analysis for NEMS Relays	E. Acosta, *S. Almeida, **B. Osoba and **T.J. King Liu
Bandgap Deformation Potential for Low-Energy Switching	D. Zubia1, A. Vidana1, M. Martinez1, S. Almeida2 and J. Mireles Jr.3
Characterization of ON -State Resistance in Body -Biased NEM Switches	Steven Patrick Chan, Benjamin Osoba, Alice Ye, Tsu -Jae King Liu

Appendix K: 2017 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
	Total Number of Respondents	20	21	26	29	22	24
	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
	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
	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
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
	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
	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

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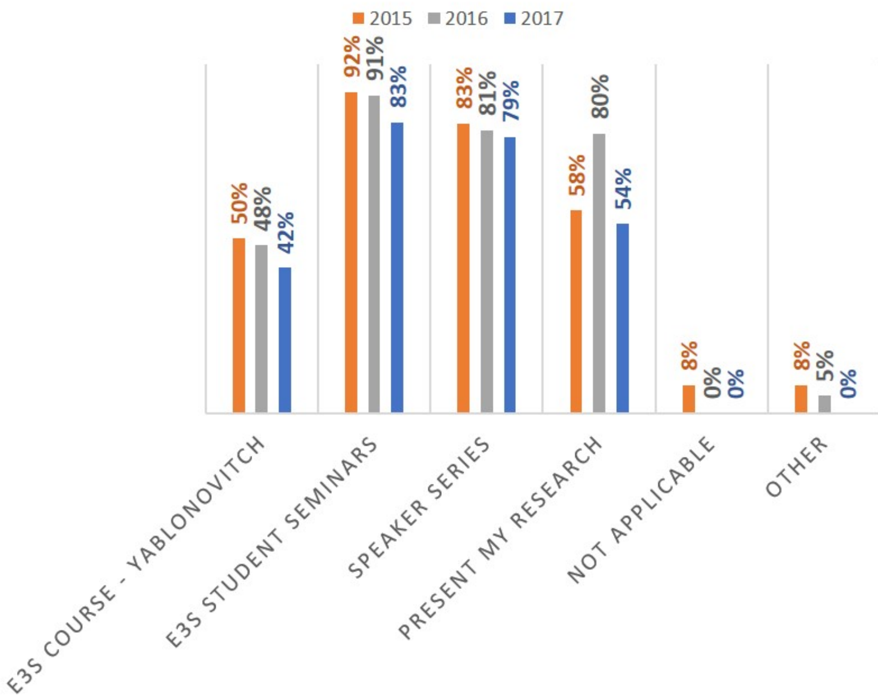
Communication	The Leadership Team keeps Center members well informed as there is a clear and timely communication on all Center activities.	4.2 ± 0.5	4.2 ± 0.6	4.7 ± 0.6	4.2 ± 0.8	4.4 ± 0.8	4.5 ± 0.5
Collaboration	The Leadership Team provides a research environment that is collaborative.	4.2 ± 0.7	4.2 ± 0.7		4.3 ± 0.8	4.3 ± 0.8	4.5 ± 0.6
	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
	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
	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
	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
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
	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
	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
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
	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

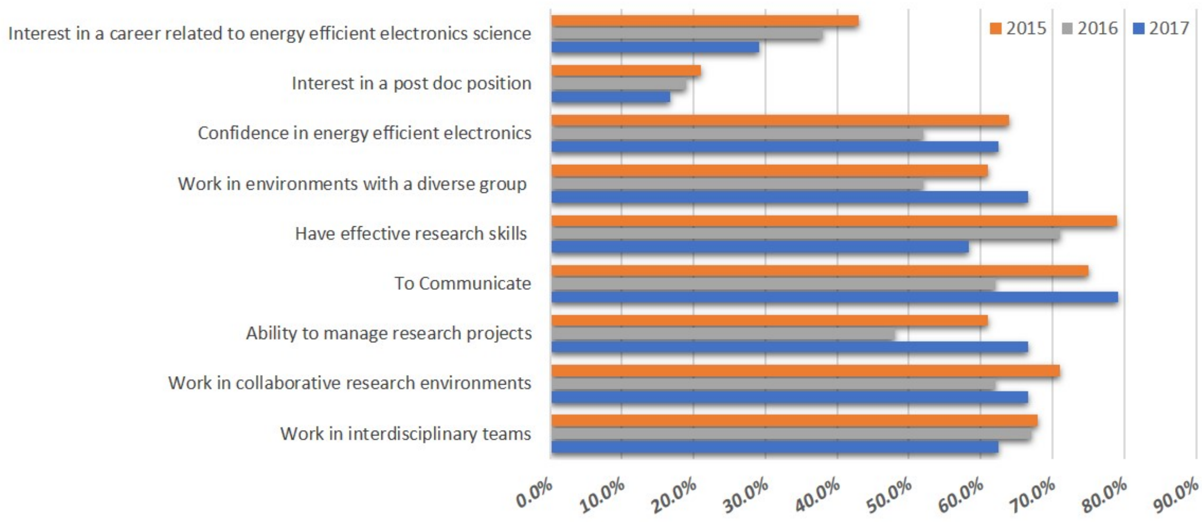
Part B: Effectiveness of the Center's Activities

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



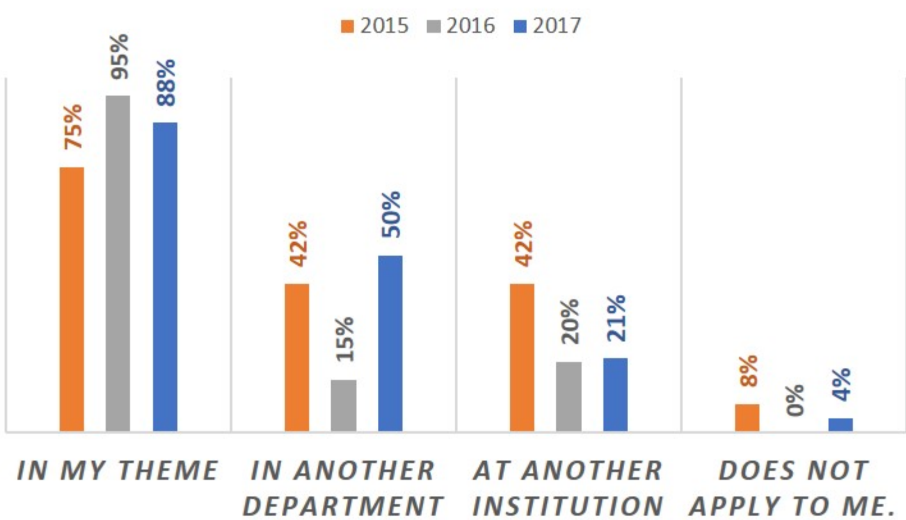
2. Respondents felt that the Center communicates with them effectively and in a timely manner using the following resources.

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



Part C: State of Collaborations

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



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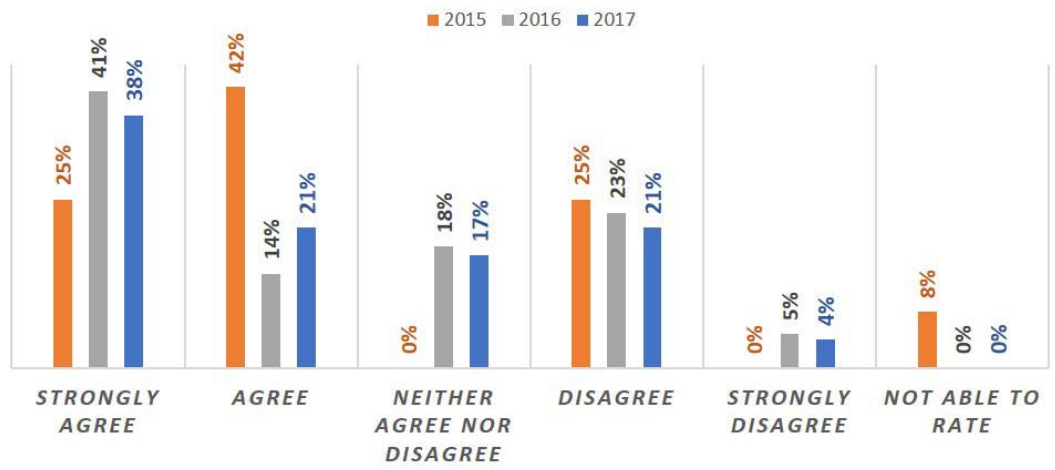
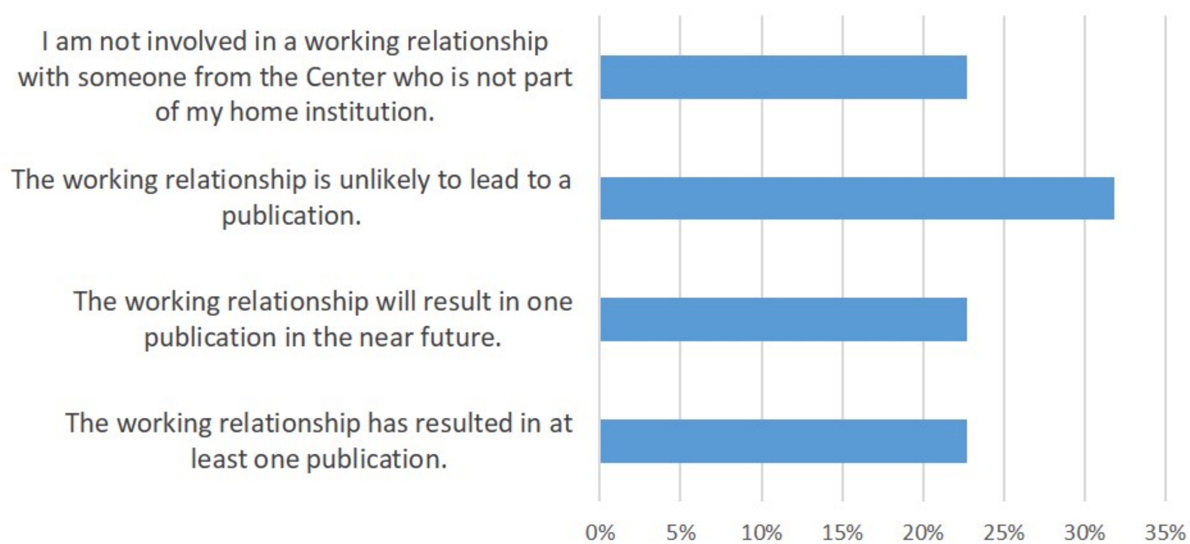
2. Respondents have developed a working relationship with someone in the Center who is not part of their home institution.



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^3S colleagues acted in an ethical manner.

Appendix L: 2017 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**
Creating an inclusive work environment.	4.9±0.2	4.9±0.2	4.8±0.4
Promoting a work environment that values and encourages teamwork.	4.9±0.3	4.9±0.2	4.8±0.4
Providing open and timely communication to me.	4.7±0.6	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
Making decisions that are in the best interest of the Center.	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
Providing tools that facilitate collaboration.	4.6±0.6	4.7±0.5	4.7±0.6
Educating a diverse generation	4.9±0.3	4.9±0.3	4.8±0.4
Identifying fundamentally new concepts and scientific principles	4.9±0.2	4.8±0.4	4.8±0.4

2017 sampling size: 18

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