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Center for Energy Efficient Electronics Science

Final

Period 10 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

TABLE OF CONTENTS

I. GENERAL INFORMATION

1a. Center Information

Date submitted	January 28, 2020
Reporting period	March 1, 2019 – February 29, 2020
Name of the Center	Center for Energy Efficient Electronics Science (E^3S)
Name of the Center Director	Eli Yablonovitch
Lead University	University of California, Berkeley
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Center URL	https://e3s-center.berkeley.edu/

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.

Institution Name	Massachusetts Institute of Technology (MIT) Vladimir Bulović
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Role of Institution at Center	MIT is a lead research, education, and outreach partner.

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

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

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

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

1b. Biographical Information of New Staff and Faculty

Please see Appendix A for biographical information for the new E^{3}S Associate Director of Education, Nicole McIntyre, and for one new faculty member, Osama Mohammed, Distinguished Professor and Associate Dean for Research in the College of Engineering and Computing at Florida International University (FIU). This step was necessary because E^{3}S senior investigator Sakhrat Khizroev moved from FIU to the University of Miami in this period. Given that the Center is currently already in its sun-setting period, it was decided to keep the E^{3}S research project and all E^{3}S supported students at FIU. While the project will continue to be guided by Sakhrat Khizroev, Osama Mohammed will formally oversee the day-by-day E^{3}S research activities at FIU. There has not been a change in research direction at FIU.

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), a Science and Technology Center funded by the U.S. National Science Foundation, was established in 2010 with the goal of revolutionizing information processing by developing next-generation electronic systems approaching the theoretical limits of energy efficiency in logic switching. Since then, E^3S has made significant contributions in the development of next-generation ultralow energy switching concepts by identifying barriers, revolutionary concepts and scientific principles that enable transformative and fundamentally new digital-information processing science. Indeed, recent advancements in cloud computing, social networking, mobile internet and data analytics, and the associated increase of battery powered electronic systems, have shown that the Center's original research goal of replacing the conventional transistor with ultralow-power switches is now as relevant as ever.

The Center for E^3S applies a multi-faceted approach, including research, education, diversity, outreach and knowledge transfer activities in pursuance of its. At the heart of the Center's activities lies the education of a diverse generation of future leaders, researchers, educators, and technicians in electronics and information technology. In fact, central to the Center's research and education mission is a collaborative approach, involving engineers, chemists, physicists, and materials scientists from five top universities. Using a four-pronged approach, involving nanoelectronics (theme I), nanomechanics (theme II), nanophotonics (theme III), and nanomagnetics (theme IV), E^3S seeks to establish the science and fundamental knowledge needed for developing highly energy-efficient logic switches.

The multi-institutional structure of E^3S is comprised of the University of California, Berkeley (*Berkeley*), Massachusetts Institute of Technology (*MIT*), Stanford University (*Stanford*), University of Texas at El-Paso (*UTEP*), and Florida International University (*FIU*). These five core institutions are supported by industry-leading companies, including Applied Materials, IBM, Intel Corporation, HP Enterprise, and Lam Research. In addition, the Center for E^3S has established strong ties with the California Community College System to provide educational outreach and train the next generation of researchers in low-energy electronics. In general, the Center for E^3S envisions a legacy promoting the application of its research and education outcomes as foundation for future ultralow-energy logic systems.

The need for energy-efficient logic systems is driven by increasing importance of cloud computing, mobile internet, data analytics, wireless sensor swarms, body-centered networks, data centers and servers, and supercomputers. While conventional transistors were the key for forging this revolution in an interconnected society, the required high powering voltages of ~0.7 volts make them unsuitable for tomorrow's mobile "off-the-grid" applications. In fact, at the most fundamental level, today's energy used to manipulate a single bit of information is orders of magnitudes higher than theoretical limits. For example, the wires connecting the transistor could operate with a very good signal-to-noise ratio at voltages ~8 mV. Since power consumption is proportional to the square of operating voltage, the energy currently used to manipulate a single bit of information is four orders of magnitude greater than needed—the difference of charging a cell phone once a day, or once every 30 years!

As the energy in current data processing is related to charging and discharging the communication wires of conventional chips, additional power-savings can be achieved by pursuing an optical communication strategy and replacing some longer metal interconnects with optical waveguides. In addition, a more sensitive, lower-voltage switch providing energy-efficient on-chip communication interconnects is needed as successor to conventional technologies.

The Center for E^3S was formed nine years ago to address these very challenges and respond to the critical need for fundamental and conceptual breakthroughs in the underlying physics, chemistry, materials science and device engineering. Now, entering its last six months of funding, the Center for E^3S prides itself on the scientific influence it will continue to have on the future science and technology of energy efficient electronics. For example, the nanoelectronics theme has found that low-power tunnel-field effect transistors will be much more challenging to create, than expected. Nonetheless, researchers at E^3S have laid out the requirements that will guide future research, including atomic scale perfection and non-Lorentzian spectral lineshape, with graphene nanoribbons as the material base. The nanomechanics theme has demonstrated the importance of molecular functionalization on the surfaces of NEM switches that will likely become standard in the field of nanomechanics. Research in the nanophotonics theme has demonstrated that the antenna-LED is the missing link of optoelectronic sources for on-chip optical communication. The antenna-LED operates at low power, but at a speed comparable or faster than lasers. The nanomagnetics theme has pointed the correct path for high-speed magnetic switching, increasing switching speed by 100 times, down to the picosecond range.

Strategic Research Plan & Rationale

From its inception, the Center for E^3S 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.

The Center recognized early on that new, ultra-low energy logic systems must meet a set of key specifications to be of practical use. The three most important requirements for the logic switch are:

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

The requirements for ultralow energy optical communication are:

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

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^3S 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. The Center's research theme strategies and approaches are outlined below.

Theme I: Nanoelectronics

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

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

In period 10, the nanoelectronics theme has continued research efforts toward 1) gaining in-depth understanding of interfacial effects and trap-assisted tunnel leakage, 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 and finFET structures fabricated in the **del Alamo** group (*MIT*). Current experimental goals are to optimize fabrication of sub-10 nm vertical nanowire III-V TFET and finFET 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. The **Yablonovitch** and **Louie** (both *Berkeley*) groups are investigating the fundamental spectroscopic sharpness of tunneling energy levels, with the emphasis on the spectral wings controlling steepness and ON/OFF ratio.

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

Theme II: Nanomechanics

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

In period 10, the goals of the nanomechanics research in the groups of **Tsu-Jae King Liu** and **Junqiao Wu** (both *Berkeley*) have remained the minimization of hysteresis voltage of NEM switches by further minimizing contact stiction and investigating relays characteristic at cryogenic temperatures. The **Liu** group, in collaboration with the group of **Vladimir Stojanović** (*Berkeley*), has also continued to further improve NEM relay-based integrated circuits operating below 100 mV.

The squitch concept, which is pursued by the groups of **Jeffrey Lang**, **Vladimir Bulović**, **Farnaz Niroui**, and **Timothy Swager** (all *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 investigate squitch performance longevity, eliminate electromigration, and study properties of molecular layers. The third electromechanical switching concept developed and investigated in the nanomechanics theme is the stritch device, a joint project between **David Zubia** (*UTEP*) and the **Liu**, **Wu** and **Javey** groups (all *Berkeley*). In this device, the stretching of the semiconductor chalcogenide material by electromechanical actuators causes straining of a 2D chalcogenide layer. This results in tensile strain and concomitant change in the chalcogenide bandgap and conductivity. Current research is focused on fabrication and testing of a newly designed actuator, which should enable stretching of the 2D monolayers by more than 3 percent.

Theme III: Nanophotonics

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

In period 10, the groups of **Ming Wu** and **Eli Yablonovitch** (both *Berkeley*) and **Jeehwan Kim** (*MIT*) have continued to optimize design and properties of antenna enhanced nanoLEDs and efficient coupling of their emission into single mode optical waveguides. The goals in this period have been to explore the fundamental limits of antenna enhanced spontaneous emission rate in comparison to the rate of stimulated emission of a laser, and to fabricate and test a fully waveguide-coupled cavity back slot antenna-LED.

Theme IV: Nanomagnetics

The nanomagnetics theme focuses on developing current-driven magnetic elements for electrical communication with switching energies at the atto-Joule level and ultrafast switching speeds (below 10 picoseconds). To achieve this, the E^3S team, led by **Jeffrey Bokor** (*Berkeley*), takes advantage of spin-transfer torque magnetic tunneling junctions and newly discovered ultra-sensitive current driven switches employing spin-orbit torque (spin-Hall effect) to switch a magnet [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 [13]. On the circuit/system level, the E^3S nanomagnetics theme has focused on developing in-memory and normally-off computing strategies using magnetic nonvolatile devices. The goal has been to evaluate the use of SRAMs enhanced with nonvolatile spin devices in general-purpose processing applications.

In period 10, the groups of **Jeffrey Bokor** and **Sayeef Salahuddin** (both *Berkeley*) have continued to focus on scaling ultrafast magnetic switching into the nanometer scale. Based on calculations, energies and currents for the electrical switching of magnets could be in the femto-Joule and micro-Amps range, respectively, for a $(20\ nm)^3$ cell size. These values would be suitable for integration with CMOS transistors. Meanwhile, the **Salahuddin** group has continued to understand the fundamental nature of spin transport and spin angular momentum transfer in spin-orbit coupled heterostructures. In the current period, the focus has been on exploring a new concept of exploiting synthetic anti-ferromagnets to induce switching in spin-orbit-torque devices without needing an external magnetic field. The group of **Shan Wang** (*Stanford*) studies topological effects in spin-orbit torque phenomena. The goal of the group of **Sakhrat Khizroev** (*FIU*) has been to fabricate and characterize square spin-transfer torque based magnetic tunneling junction devices with sizes smaller than 2 nanometers. In collaboration with the **Bokor** group, the nanoparticle STT-MTJ concept has been used to write information not into two but into three layers and used the tunneling MR effect to read back information, paving the way for a new computing paradigm, which uses spin polarized currents to write and read back multilevel signal information.

Education & Diversity Strategic Plan

A central pillar of the Center's mission is education and broadening participation. The Center's vision is to leave a legacy 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. The Center pursues this by working to increase the number of students pursuing STEM education at all levels, especially in technical disciplines related to energy efficient electronics science. In addition to creating a pipeline of future graduate students, postdocs, and faculty trained in energy efficient electronics science, these efforts will prepare students for technical disciplines beyond those in the Center, and for the future STEM workforce in general.

The Center has established a full menu of education programs, which educate and develop high-school seniors, community college students, upper division undergraduates, graduate students, postdocs, and community college faculty members.

Graduate Education

The Center provides formal and informal education opportunities for our graduate students. Since period 1, E^3S Director, **Eli Yablonovitch** (*Berkeley*) has taught a graduate level course each year at UC Berkeley. This course allows Center member and non-member graduate students to receive academic credit for training in low energy electronics. The course includes a strong focus on E^3S topics and perspectives. Additionally, Center faculty have incorporated low energy electronics and topics specific to the Center's research approaches into their other courses.

Center students and postdocs participate in informal training in the forms of numerous presentations, mentoring, science communications, and other leadership opportunities. Given the number of opportunities available, the Center developed the E^3S Professional Development Program (E^3S PDP) to guide students and postdocs to acquire a diverse and balanced set of experiences. The program provides students and postdocs with a Leadership Certificate if they participate in many of the professional development opportunities. The Center also offers training in areas that it deems important in the development of a scientist/engineer. Incoming students and postdocs are given ethics training when they begin in the Center. Additionally, all mentors of REU students receive training in mentorship, project management, and working with diverse groups. The Center has offered training in topics like publishing scientific results, entrepreneurship, science communication, proposal writing, and best practices to promote diversity.

Undergraduate Education

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

- The ETERN program provides undergraduates from E^3S member institutions with a paid research internship with E^3S faculty.
- The E^3S REU program provides a paid summer research experience to students from 4-year institutions not associated with the Center.
- The Transfer-to-Excellence (TTE) REU program provides California community college students with a paid summer internship to conduct research with E^3S and E^3S-affiliated faculty at UC Berkeley.

The Center has relied on these programs to develop undergraduate researchers and build a diverse pipeline of graduate students. In particular, the Center chose to focus on California community colleges because the system is the largest in the US and enrolls many students from backgrounds underrepresented in science and engineering, including women, underrepresented minorities, students with disability, veterans, Pell grant recipients, and first generation college students. After eight years of operation, the Transfer-to-Excellence (TTE) program boasts high transfer rates to STEM baccalaureate programs, including 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 94%, with most transferring to Tier 1 research universities.

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 not as high as we would like. 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, and working towards promoting and sustaining a climate of inclusive excellence through workshops and faculty meetings.

The Center also seeks to impact community college education by offering professional development opportunities to community college faculty. Since 2012, community college faculty members have joined the laboratories of E^3S faculty each summer. Additionally, they develop new teaching materials to expand science and engineering course offerings at their community college. These processes are advised by E^3S graduate students or postdocs. The community college faculty participants are expected to implement new curriculum in their classroom upon their return to their home institution and many have returned in subsequent summers to develop additional courses.

Online Education

Since period 4, the Center has worked to create an educational legacy that will be publically accessible and digestible after the Center sunsets. Through our eBook, video series, and use of the NanoHub collaboration platform, the Center's collaborative research will be accessible to consumers of a wider diversity of backgrounds. The video series consists of lecture modules taught by graduate students and is currently undergoing final review and editing. The Theme II eBook is complete and authors are seeking final approval for included figures and tables. The other three eBooks are in the drafting and internal peer review process. In addition to the impact these materials will have on non-affiliates, creating these online resources has been an important professional development experience for the Center' graduate students, postdocs, and staff.

Additionally, Center staff developed and debuted a new online mentoring program in Period 10. After their participation in the Transfer-to-Excellence REU program, thirteen California community college students engage in monthly mentoring conversations with faculty (1), post-docs (6), graduate students (5), and undergraduate students (1) in their field.

Knowledge Transfer

Knowledge transfer is at the heart of the Center for E^3S mission as an NSF Science and Technology Center. E^3S is dedicated to search for groundbreaking scientific discoveries and fertilize new technologies, and associated knowledge transfer activities and outcomes are considered a key metric of its success. Since its inception, the Center for E^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 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 10

In this section, a summary of the progress of the Center for E^{3}S in period 10 is presented. Details and in-depth analyses of the results are given in the following sections of this report.

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

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

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
Research	Multi-PI projects	P2: 30% P5: 75% P6: 50% P7: 60% P8-P10: 70%	44%	67% (14)	55% (12)	64% (14)	76% (13)	65% (11)	79% (15)	89% (16)	88% (15)
Research	Multi-Institutional projects	P2: 10% P5: 30% P6: 15% P7: 20% P8-P10: 25%	4%	10% (2)	9% (2)	23% (5)	29% (5)	29% (5)	32% (6)	72% (13)	53% (9)
Research	Publications with authors from multiple institutions	P3: 12 P4: 3 P5-10: 5	0	0	1	1	4	4	3	3	5
Research	New joint research funding awards	P6: 1 P7: 0 P8-P10: 1	(new for P6-10)				0	3	1	1	2
Education	Center graduates completed E^{3}S training	P2: Baseline P3-5: 50% P6: 15% P7: 30% P8: 40% P9: 50% P10: 15%	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)	5 (36%)	3 (23%)	7 (58%)

	E^3S graduate students taking online course taught by Center director	P6, 8, 10: 0 P7, 9: 10	(new for P6-10)				0	8	0	6	3
	Undergraduates who pursue advanced degree in science and engineering	P3: 5% P4: 30% P5: 35% P6: 40% P7: 45% P8-P10: 50%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)	36 (69%)	41 (73%)	47 (70%)	51 (71%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P2: Baseline P3: 5% P4-5: 80% P6-10: 85%	n/a	3 100%	6 100%	7 100%	6 100%	4 80%	4 60%	6 100%	6 100%
	Pre-college students who pursue a bachelor's degree in science and engineering	P3: Baseline P4-5: 70% P6-10: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)	180 (47%)	Program ended	
	Students and postdocs serving in leadership roles in the Center	P2: Baseline P3: 15% P4: 20% P5: 25% P6-8: 30% P9: 20% P10:15%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)	14 (16%)	17 (21%)	17 (25%)
Diversity	Women in the Center's research programs	P2: Baseline P3: 5% P4: 30% P5: 20% P6-10: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)	12 (14%)	20 (23%)	18 (16%)
	Under-represented minorities in the Center's research programs	P2: baseline P3: 15% P4: 5% P5-6: 10% P7-8: 12% P9-10: 15%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)	11 (13%)	15 (17%)	11 (15%)

	Participants from under-represented* groups in the Center's Diversity programs	P3: Baseline P4: 80% P5-10: 85%	n/a	n/a Total 93 (82%)	Women 37 (44%) URMs 58 (68%) Total 73 (86%)	Women 26 (41%) URMs 36 (56%) Total 49 (77%)	Women 29 (40%) URMs 49 (67%) Total 66 (90%)	Women 25 (40%) URMs 38 (60%) Total 63 (87%)	Women 38 (44%) URMs 48 (55%) Total 69 (80%)	Women 40 (42%) URMs 50 (58%) Total 68 (77%)	Women 40 (35%) URMs 45 (64%) Total 70 (79%)
	Undergraduate participants from under-represented* groups pursuing advanced degrees in disciplines related to the Center	P6: 40% P7: 45% P8-P10: 50%	(new for P6-10)				17 (55%)	23 (54%)	27 (50%)	30 (55%)	32 (53%)
	Community College students from under-represented* groups pursuing a science or engineering baccalaureate	P6-10: 85%	(new for P6-10)				16 (70%)	22 (81%)	24 (80%)	30 (88%)	36 (90%)
	Pre-college participants from under-represented* groups pursuing a bachelor in science or engineering	P6-10: 80%	(new for P6-10)				73 (55%)	102 (63%)	14 (33%)	Program ended	
Knowledge Transfer	Center publications	P2-5: 18 P6-7: 25 P8-P10: 30	22	21	27	48	39	36	33	33	32 (6 subm)
	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26	21	22
	Center sponsored symposia & workshops	P2: Baseline P3: 0 P4: 1 P5: 0 P6: 2 P7-9: 1 P10: 2	1	0	1	0	1	1	2	2	2

	Citations of publications *(cum)*	P3: 10 P4-5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase	6076 40% increase	9447 55% increase
	Industry contacts:										
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38	41
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8	7	7
	Patent disclosures										
	• Disclosure/ Provisional	P3: 3 P4: 3 P5: 5 P6: 2 P7: 2 P8: 3 P9-P10: 4	1	0	1	0	2	1	4	0	4
	• Patent/Patent Application	P4: 0 P5: 3 P6: 1 P7-P9: 2 P10: 3	1	2	1	3	8	4	1	2	2
	Technologies attributable to Center's research										
	• Low energy devices	P6-P9: 0 P10: 1	(new for P6-10)				0	0	0	0	0
	• Enabling other applications	P6-7: 0 P8-P9: 1 P10: 2					0	0	0	1	1
	Center's alumni into relevant industries	P5: 50% P6-7: 30% P8-P9: 40% P10: 50%	Student 0%	Student 64% (7)	Student 16% (2)	Student 16% (6)	Student 50% (12)	Student 22% (2)	Student 33% (4)	Student 22% (2)	Student 38% (3)
			Postdoc 100% (1)	Postdoc 33% (2)	Postdoc 20% (2)	Postdoc 40% (4)	Postdoc 13% (1)	Postdoc 18% (2)	Postdoc 60% (3)	Postdoc 0	Postdoc 67% (4)
		P6-10: 30%	(new for P6-10)				Student 38% (9)	Student 78% (7)	Student 58% (7)	Student 56% (5)	Student 50% (4)

	Center's alumni pursuing research in academia & research labs in disciplines related to the Center						Postdoc 88% (7)	Postdoc 82% (9)	Postdoc 40% (2)	Postdoc 83% (5)	Postdoc 33% (2)
Center Management	Annual Surveys (measured and reported on Likert Scale)										
	• Students /Postdocs	P2-5: 3 or higher P6-10: 4 or higher	3.9±0.2	4.0±0.3	4.2±0.2	4.5±0.2	4.3±0.2	4.3±0.3	4.4±0.1	4.3±0.2	4.6±0.3
	• Co-PIs		No survey	Leader-ship 4.46	Leader-ship 4.7±0.5	Leader-ship 4.9±0.1	Leader-ship 4.6±0.1	Leader-ship 4.8±0.2	Leader-ship 4.8±0.1	Leader-ship 4.8±0.1	Leader-ship 4.6±0.1
	• External Advisory Board		Strategic Plan: 4.2 Center Status 4.0	Strategic Plan: 4.1 Center Status 4.0	Strategic Plan: 4.6 Center Status 4.6	Strategic Plan: 4.4 Center Status 4.7	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	N/A
	Authorship disputes	P2-5: 20% decrease P6-10: 0	0	0	0	0	0	0	0	0	0
	Plagiarism	P2-10: 0	0	0	0	0	0	0	0	0	0
	Changes in Center processes made in response to evaluation results	3 months for closure of regular action; 1 week for closure of time-sensitive action	(new for P6-10)				0	0	0	0	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 10

The Center for E^3S 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 10, the Center's faculty researchers have been:

- *Berkeley*: Jeffrey Bokor, Felix Fischer, Ali Javey, Tsu-Jae King Liu, Steven Louie, Sayeef Salahuddin, Vladimir Stojanović, Junqiao Wu, Ming C. Wu, Eli Yablonovitch
- *MIT*: Vladimir Bulović, Jesus del Alamo, Jeehwan Kim, Jing Kong, Jeffrey Lang, Farnaz Niroui, and Timothy Swager
- *Stanford*: Shan Wang
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

Theme I: Nanoelectronics – Key Accomplishments

- *III-V Nanowire TFETs:* For the study of the underlying physics of tunneling in semiconductors, vertical nanowire (VNW) III-V TFET and finFET structures developed by the **del Alamo** group have proven to be excellent model systems [2, 14, 15]. In particular, these systems give insights into the issue of defect assisted tunneling in the OFF-state. In this period, the **del Alamo** group carried out a detailed study of excess OFF-state current due to band-to-band tunneling and the floating-body effect in InGaAs FinFETs. These mechanisms affect the subthreshold behavior of all field-effect transistors based on narrow bandgap materials with a floating body, regardless of their structure. The group has developed a simple model of the parasitic bipolar effect (PBE) in InGaAs FinFETs, which captures the key gate length and fin-width dependences. The model accounts for surface recombination at the sidewalls of the fin as well as bulk recombination at the heavily doped source. When compared with experimental results, the model suggests that fin sidewall recombination dominates in long gate length transistors and leads to an exponential gate length dependence of the current gain on the parasitic bipolar junction transistor (BJT). The model enables the extraction of the carrier diffusion length, which exhibits the predicted fin-width dependence. For short gate length transistors, source recombination dominates, and the parasitic bipolar gain scales with the inverse of the gate length.

  Finally, the **del Alamo** group has also continued research on the potential of in-situ atomic-layer etching and atomic-layer deposition of the gate dielectric for advanced 3D transistors by carrying out a detailed characterization study of InGaAs FinFETs fabricated by this new technique. They found very significant improvements in both the ON- and OFF-state characteristics of highly scaled InGaAs FinFETs when compared with identical devices fabricated in a conventional way. This suggests both a reduction in interface state density that affects the subthreshold swing and a smoothing of the InGaAs surface that enhances electron transport. Our study dramatically illustrates the extraordinary potential of our new technique for all manner of devices in all material systems.

- *Layered Chalcogenide TFETs:* Recognizing that sharp subthreshold swings in 2D-transition metal dichalcogenide (TMDC) TFETs can only be achieved by highest quality chalcogenide materials, the **Kong** group started to use CVD for the growth of large area 2D monolayers. In this period, the **Kong** group made significant progress by growing large area, single-crystalline monolayers MoS_2 flakes of ~500 μm size. The group has also investigated the direct patterning of MoS_2 during the synthesis step. This method showed the potential of using the pre-patterned substrates as a master template for the repeated growth of monolayer MoS_2 patterns at a spatial resolution of 2 μm with excellent homogeneity. In addition, the **Kong** group has developed a MoS_2 based ferroelectric field-effect transistors (FeFETs) using its CVD synthesis method, which is scalable and a manufacturing-compatible process. MoS_2 was used as a resistive switching channel for the FeFETs in which the MoS_2 channel is modulated by a hybrid gate stack of HfO_2/ferroelectric $HfZrO_x$ thin films. The programming processes in the 2D MoS_2 FeFETs originate from the ferroelectric polarization switching, yielding two distinct write and erase states for data storage and cumulative channel conductance for artificial synapse applications. The 2D FeFETs displayed a low-voltage-driven feature (< ±3 V) and gate-tunable ferroelectric hysteresis characteristics. This work opens an avenue for future energy-efficient "brain-on-a-chip" hardware.

- The group of **Ali Javey** has focused on 2D material engineering in order to realize better device performance through material quality improvements. In collaboration with the **Yablonovitch** group, the team developed a method to increase the photoluminescence quantum yield of as-exfoliated MoS_2 and WS_2 monolayers to near unity by electrostatic doping, without any chemical treatment [16]. Remarkably, this work demonstrated that, even in the presence of defects in sulfur-based TMDCs, neutral exciton recombination could be entirely radiative. In addition, the **Javey** group succeeded in directly patterning monolayer TMDCs without the use of a sacrificial resist [17]. Using scanning probe lithography, a negatively biased tip was brought close to the TMDC surface. By inducing a water bridge between the tip and the monolayer surface, controllable oxidation is achieved at the sub-100 nm resolution. The oxidized flake is then submerged into water for selective oxide removal, which leads to controllable patterning. This resist-less process results in exposed edges, overcoming a barrier in traditional resist-based lithography and dry etch where polymeric byproduct layers are often formed at the edges.

- *Graphene Nanoribbon Quantum Tunneling Structures:* The group of organic chemist **Felix Fischer** has continued to lead the experimental aspects of this project with broad theory support by **Steven Louie** and **Eli Yablonovitch.** In addition, the group of **Jeffrey Bokor** provides guidance in integrating GNRs into FET device architectures. In this period, the team successfully demonstrated that symmetry protected topological states can be rationally engineered into GNRs featuring a metallic band structure. They showed that symmetric placement of half-occupied zero-mode states in a 1D superlattice gives rise to extended metallic bands embedded in an otherwise insulating GNR backbone. The team further demonstrated that the resulting 1D metallic bandwidth could be tuned over a large energy range (from 20 meV to 500 meV) through deliberate sublattice symmetry breaking via a thermally activated pentagonal ring closure. This work points to a new strategy for realizing not only 1D metallicity, but also 1D magnetism and other highly correlated 1D phenomena that may arise from a tunable 1D density of states at the Fermi energy (EF). This technology also represents a new strategy to access unusually sharp energy levels ($\Delta E \sim 5$ meV). Such sharp energy levels were recently identified by the **Yablonovitch** group as critical to the successful realization of TFET architectures.

  The **Louie** group revealed through first-principles calculations that by applying an experimentally accessible transverse electric field, certain designer GNRs develop tunable topological phases. By applying a periodic spatially varying field, junctions of GNRs between distinct topological phases can be created, with localized topological interface states emerging at these junctions. For example, they found that a boron and nitrogen dimer co-doped armchair GNR with the number of carbon atoms N=11 in the width direction exhibits such tunable topological phases. These discoveries provide design principles for tunable topological flat bands in GNRs using transverse electric fields forming such superlattices. By modifying the profile of the transverse electric field applied on the GNR, the bandwidth and metallicity of the GNR superlattice may be tuned, so that it may be used as building blocks for low-energy consumption TFETs.

Theme II: Nanomechanics – Key Accomplishments

- *Ultra-Low-Voltage Relay Design and Operation:* The **Liu** and **Wu** groups continued to focus on further improvements of the NEM relay design and low-voltage operation with the goal of reducing both the relay switching hysteresis voltage (VH) and sub-threshold swing. In this period, the team made an important discovery: It was found that relays can be operated even more reliably, with sub-25 mV voltage signals, at temperatures below 100 K. This is the result of a dramatic reduction in hysteretic switching behavior and elimination of contact oxidation at cryogenic temperatures. At cryogenic temperatures the NEM relays switched on and off abruptly with sweeping gate voltage, and hysteresis voltages as low as 4 mV were observed at 4 K, which is approximately two orders of magnitude lower than for MOSFETs. Another important relay feature, which is positively impacted at cryogenic temperatures, is contact oxidation. Since 90 K is the boiling point of oxygen gas, sub-90 K operation inhibits the formation of native oxide on the electrode surfaces and thereby allows low on-state resistance, R_{ON}, to be maintained. For relays operated at liquid nitrogen temperature (77 K) or liquid helium temperature (4 K), the endurance of a relay exceeds 10^8 cycles, which is two orders of magnitude higher than at room temperature. The demonstration of successful relay operation at temperatures down to 4 K makes MEM relay ICs advantageous for implementation of digital logic with ultra-low power dissipation for cryogenic applications such as quantum computing.

The group of **Junqiao Wu** (*Berkeley*) continued the collaborative work with the **Liu** group in using molecular layers to further reduce surface adhesion of NEM switches without degrading their conduction. Recently, the team used self-assembled molecular coatings with branched tails to preserve conduction, while the density of fluorine atoms can be increased by adding more branches to the molecule to reduce adhesion. The best results were obtained by the branched self-assembled molecular coating perfluoro(2,3-dimethylbutan-2-ol) with 24 fluorine atoms per nanometer. This perfluoro molecule is <0.5 nm long and as such does not degrade conduction substantially. By using this perfluoro coating, a 62 percent reduction in hysteresis and 52 percent reduction in average switching slope was achieved, while the instantaneous switching slope was not greatly affected.

- *Sub-100 mV Relay-Based Digital Integrated Circuits:* The **Liu** group in collaboration with the **Stojanović** group has continued research into demonstrating reliable operation of relay-based digital integrated circuits (ICs) at voltages below 100 mV. The goal remains to prove their suitability for ultra-low active power consumption as well as zero static power consumption. 50-mV operation of digital ICs at room temperature was demonstrated for the first time, enabled by an improved relay design and self-assembled molecular coating to provide for lower contact adhesion to reduce hysteretic switching behavior. In addition, tremendous improvement of relay-based digital IC characteristics was achieved under cryogenic conditions (77 K). Waveform analysis revealed proper circuit operation at 300 K with 100 mV signals, while proper circuit operation at 77 K was achieved with <25 mV signals, made possible by smaller hysteresis voltages.

- *Squitch: Molecular Squeeze-Switch:* The **Bulović**, **Lang** and **Swager** groups, the **Squitch** team, has continued work on improving squitch yield and performance, investigating the mechanical behavior of the molecular films as they cyclically compress and elongate during switching, and exploring graphene-based two-terminal squitches. The team noticed a slow upwards drift in current for a given voltage as the switching cycle count increases and hypothesized that this current drift is the result of either a permanent compression of the molecule layer in the tunneling gap, or perhaps a parting of the layer. By examining a cross-sectioned squitch with transmission electron microscopy, it was found that a small filament or bump of gold had formed on the lower electrode, which might have been the result of gold electromigration from the lower electrode into the tunneling gap. To eliminate electromigration the group has started to explore electrodes, which cannot support this phenomenon, such as graphene electrodes. Correspondingly, the team developed an all-graphene two-terminal squitch fabrication process flow, which uses many of the fabrication process steps already developed for the previous fabrication process. In the new squitch design, the vertically-moving top electrode is fabricated from graphene. Further, by transferring the graphene electrodes in all squitches in a single aligned step, fabrication yields as high as 80 percent are achieved. Squitches of this type with a PEG molecular layer have been successfully fabricated and displayed a lower than typically observed turn-on voltage.

  In this period, the **Squitch** team has also investigated the behavior of squitches fabricated with different self-assembling molecular layers to determine whether molecular engineering is a viable approach to improving and ultimately tuning squitch performance. The team investigated four different molecules, which were all designed to be approximately 3 nm long in their relaxed state and are terminated with a thiol group so as to self-assemble onto gold bottom electrodes. These molecules were selected to have different stiffness values. Indeed, characterization of squitches fabricated with the four molecules revealed significant differences with the stiff molecular layer exhibiting very little, if any, compression as viewed through squitch current, while the much softer molecular layers exhibit considerable mechanical compression. More importantly, the team showed that fine-tuned molecular-layer properties could significantly increase squitch performance and longevity. As a result, the team will continue to pursue molecular engineering as an important component of squitch development.

- *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, the **Zubia** group redesigned the actuator to account for previous issues, including vertical actuation, which limited the strain to a maximum of 3%. The new actuator design consists of a thin and long movable beam anchored at opposite ends (sources). Actuation of the beam is achieved by applying a voltage to the gate with respect to the source terminals, (V_{GS}). A MoS_2 flake is clamped across the drain and center of the beam and then stretched when V_{GS} is applied. The current fabrication process using a new mask consists of the following steps: (1) patterned photoresist, (2) nickel deposition and liftoff, (3) deep reactive ion etching (DRIE) of top silicon device layer, (4) transfer and clamping of TMDC onto MEMS, and (5) device release. The DRIE etching was performed in the lab of **Jose Mireles** at the Universidad Autonoma de Ciudad Juarez, who functions as an external collaborator.

Theme III: Nanophotonics – Key Accomplishments

- *Antenna-Enhanced III-V nanoLEDs:* The **Wu** and **Yablonovitch** groups at Berkeley have continued to investigate and optimize the efficiency and direct modulation rate of the III-V antenna-LED developed at E^3S [18, 19]. In particular, the team has explored the fundamental limits of antenna enhanced spontaneous emission rate in comparison to the rate of stimulated emission of a laser. It should be emphasized the calculated stimulated emission lifetime of 16 ps at saturation greatly exceeds the intrinsic spontaneous emission lifetime of a similar semiconductor. However, the team showed that the LED has a major advantage over the laser: in practice a laser achieves less than 10% of useful gain compared to what is theoretically feasible because of limitations on creating a population inversion, while an enhanced LED can be heavily doped to take full advantage of the dipole matrix element. This significantly reduces the constraint on the needed antenna enhancement.
  The spontaneous emission lifetime of a semiconductor with extreme p-doping and an essentially empty valence band is ~700 ps. Therefor, an enhancement factor of approximately 100x is needed for the spontaneous emission rate to exceed the stimulated emission rate, which is readily achievable in many antenna designs. Furthermore, the group showed fine-tuning the geometric antenna parameters can be used to create ultra-efficient, high-speed optical antenna-LEDs.

- *Coupling of nanoLEDs to Optical Waveguides:* The **Wu** and **Yablonovitch** groups at *Berkeley* have continued their close collaboration with the **Kim** group at *MIT* with the goal to create an optical link by coupling of the III-V antenna-LED to waveguides. To address to challenge, the team used electromagnetic design techniques to engineer and optimize coupling efficiencies of nanoLEDs to single mode optical waveguides. Building on these studies, in this period, the nanophotonics group fabricated and tested a waveguide-coupled cavity back slot antenna-LED. The **Kim** group grew all epitaxial materials with different active region designs, as specified by modeling results from the **Wu** and **Yablonovitch** groups. Successful coupling was achieved as confirmed by photoluminescence mapping and spectrum analysis. The group calculated a waveguide-coupling ratio of 85.9%. While this is a first approximation of the waveguide coupling efficiency, 3D FDTD simulations revealed that additional characterization steps are needed to directly determine the true coupling efficiency.

Theme IV: Nanomagnetics – Key Accomplishments

- *Picosecond Magnetic Switching:* The **Bokor**, **Salahuddin**, and **Stojanović** groups have joined forces to integrate magnetic device structures on advanced CMOS chips in order to realize ultrafast magnetic switching and readout triggered by electrical pulses generated directly by CMOS circuits. In period 10, research efforts have continued to address a key challenge: reduction of both the switching energy and current by scaling the magnetic switching structure into the nanoscale. Calculations revealed that energies and currents for the electrical switching of magnets could be as low as ~3.5 fJ and ~10's of μA, respectively, for a (20 nm)^3 cell size, which would be suitable for integration with CMOS transistors. While many magnetic compounds lose their important perpendicular anisotropy, the **Bokor** and **Salahuddin** groups discovered that GdCo and GdTbCo alloys maintained good perpendicular anisotropy upon scaling into sub-micrometer range. In fact, for the GdCo alloys, ultrafast all-optical switching behavior was observed in nanoscale dots fabricated in arrays down to 50 nm diameter. In order to test electrical switching of individual dots, suitable microwave circuits for delivering the required short electrical pulses to the device need to be designed. Furthermore, detecting the magnetic state of individual dots needs to be achieved. The **Bokor** group has continued to make progress in this effort, and successfully fabricated and tested a Hall-cross device geometry capable of measuring the magnetization in GdCo nanodots down to 50 nm diameter. Simulation studies of pulse propagation on microwave striplines have guided the design for the integration of this Hall bar structure into a microwave stripline that will generate the picosecond electrical pulse and deliver it to the Hall bar. Fabrication of these structures has turned out to be rather challenging and is currently still in progress.

- *Spin-Orbit Torque Switching:* In this period, the **Salahuddin** group explored a new concept of exploiting synthetic anti-ferromagnets to induce switching in spin-orbit-torque devices without needing an external magnetic field. Based on micromagnetic simulations, they showed that it is possible to achieve spin–orbit torque field-free switching of a synthetic antiferromagnet comprised of two ferromagnetic (FM) layers with perpendicular magnetic anisotropy, sitting on top of a conventional antiferromagnet [20]. Field-free magnetization reversal is propelled by the competing exchange fields and spin torques. Although some antiferromagnetic coupling is necessary to switch both ferromagnetic layers, strong Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions inhibit the switching process due to the strong repelling forces experienced by both FM layers. The switching happens through domain nucleation and propagation and is aided by Dzyaloshinskii–Moriya interactions.

  The group of **Shan Wang** (*Stanford*) focuses on experimental research for demonstrating SOT switching of adjacent ferromagnets, especially magnetic-tunnel-junction (MTJ)-compatible CoFeB and NiFe materials, in the SmB_6 and heavy metal systems. In this period, achieved room temperature high charge-to-spin conversion efficiency was achieved in sputtered WTe_x-based heterostructures that can withstand 300 °C annealing process. They successfully demonstrated damping-like SOT-induced magnetization switching using ion-beam sputtered WTe_x thin films and found that using a WTe_x/Mo/CoFeB/MgO-based heterostructure, the in-plane magnetization direction of the CoFeB layer can be detected electrically using the unidirectional spin Hall magnetoresistance (USMR) effect. The field dependence of USMR shows that the USMR effect originates from the scattering between SOT spin currents from WTe_x and magnons in the CoFeB layer. Room temperature switching with a current density of 1 MA/cm^2 has been demonstrated. The charge-to-spin conversion efficiency was found to be around 0.5 using the critical current density values.

- *Magnetic Tunneling Junction Devices:* The **Khizroev** group, in collaboration with the **Bokor** group, has continued research on spin-transfer torque (STT) MTJ devices made of ferrimagnetic $CoFe_2O_4$ nanoparticles sandwiched between magnetic layers of traditional high-anisotropy CoFeB compositions [21]. This nanoparticle STT-MTJ concept combined with electron-beam lithography nanofabrication was used to write information not into two but into three layers and the written/read back information had a ternary (not binary) signal format. In this period, the team performed detailed studies of three different read back options: giant magnetoresistance (GMR) and/or tunneling magnetic resistance (TMR) effect, the MOKE effect, and MFM-based reading from the top surface [22-24]. Because of the different physics, these three effects provide different numbers of signal levels. They concluded that the TMR effect, due to the tunneling resistance dependence on the relative orientations of the magnetizations at each interface in the 3-layer junction, is substantially simpler to implement compared to the MOKE effect. Therefore, the goal will be to improve the reading via GMR and/or TMR and increase the number of signal levels to more than three. Unlike the traditional binary signal information processing, multilevel signal processing, with more than two signal levels, is believed to be more energy efficient as well as much better suitable for realizing novel computing paradigms such as neuromorphic computing – brain inspired computing.

System Integration – Key Accomplishments

- *System Implementation of E^3S Devices—Applications in Edge Computing:* From the very start of the Center for E^3S, System Integration, under the leadership of **Vladimir Stojanović** (*Berkeley*) under was regarded as an important and integral part of its research endeavors. System Integration at E^3S overarches the four research themes (nanoelectronics, nanomechanics, nanophotonics and nanomagnatics) as an integral "control organ" and checks that the component research outcomes and new scientific device concepts of the Center will actually lead to new energy-efficient system architectures, enabling future ultra-low power information technologies. In this period, the collaborative research efforts of the **Stojanović**, **Liu**, and **Bokor** groups has continued on system integration of E^3S nanomechanical and nanomagnetic devices, which possess the opportunity for inherent non-volatility. In particular, the team has focused on the integrated circuit implementations of the systems in the so-called "edge compute" scenarios, where the sensory and computation functions are severely energy limited. The accelerator generator framework, which the **Stojanović** group put in place during the previous period, now serves as the baseline for the generation of new designs utilizing the nanomagnetic and nanomechanical devices, as well the tool for benchmarking of their performance vs. CMOS-only designs. A per-layer comparison for a state-of-the-art neural net ResNet-50 revealed 10-150x speed-ups of the structured sparsity architecture developed by the **Stojanović** group compared to unstructured sparsity state-of-the-art architectures, depending on the layer of the neural net. Similar results are found for VGG-19. Being able to quantify the application-level benefits of these emerging device technologies will hopefully both help stimulate the interest in their adoption (and further process developments required to support it), as well as provide further important guidance to E^3S researchers on the critical device design parameters that need to be further optimized for a given application and architecture.

- *Analog Machines for Digital Optimization:* In period 10, the **Yablonovitch** group started a new research project on developing continuous-time analog machines for digital optimization. Such analog machines have attracted significant interest for solving the computationally hard Ising Hamiltonian optimization problem, which describes the total interaction energy of any given network of coupled magnetic spins. The motivation for designing analog machines for the Ising problem is that there are physical principles in the domains of optics and electrical circuits and many other systems that be exploited to achieve orders-of-magnitude time speedups over digital algorithms while matching the quality of solutions obtained by them. Using a newly designed electrical LC oscillator-based Ising machine, the team solved a 32-spin system and showed that optimization of a much larger class of merit functions beyond the Ising Hamiltonian can be performed by appropriate modifications.

Education and Diversity Accomplishments in Period 10

The Center continued to offer important education opportunities to community college students, upper division undergraduate students, graduate students, postdocs, and community college professors in period 10. These opportunities included two REU programs, an RET program, an E^3S course, E^3S Rotation Program, the ETERN program, and the Professional Development Program.

The Center's two REU programs (TTE REU and E^3S REU) are intended to be pathway programs that encourage diverse students to pursue undergraduate research and graduate studies. During period 10, these programs provided 21 undergraduate students with research opportunities, 20 at UC Berkeley and one at MIT. Of these participants, 11 did research supported by the Center and/or with Center faculty. The Center has a strong record of REU program alumni transferring and furthering their careers in graduate education. To date, 94% of eligible TTE REU alumni have transferred to a four-year university to pursue a degree in science or engineering—88% of these students have been from groups underrepresented in STEM. All of the community college students who did research with E^3S or E^3S affiliated faculty last year have transferred to a four-year university. Additionally, 71% of past E^3S REU participants have enrolled in a graduate program in science or engineering.

The Center's Professional Development Program (PDP) was popular with graduate students and postdoc in period 10. More members (14) completed the certificate this year than any past year. The E^3S Rotation Program also gave one FIU graduate student the opportunity to complete research at UC Berkeley during Summer 2019. Finally, Center graduate students and postdocs have benefitted from mentoring undergraduate students and collaborating on Center legacy materials, including the eBook and a series of video lectures.

Knowledge Transfer Accomplishments in Period 10

Knowledge transfer is at the heart of the Center for E^3S mission and vision to foster groundbreaking new science discoveries and fertilize new technologies. Continuing the trend of previous years, dissemination of results and outcomes from research, education and diversity activities has remained the key knowledge transfer avenue of the Center. In period 10, E^3S has continued its strong record of knowledge transfer through a range of activities, including dissemination of results and outcomes from research and education, international meetings and workshops, social media and other new platforms to reach a broad community of scientists and engineers, and further strengthening the Center's research and education legacy.

Results from the Center's research and education activities were shared with the scientific community and general public through publications in scientific peer-reviewed journals, presentations at peer-reviewed conferences, scientific meetings, universities and industry, and knowledge exchange with a wide range of communities via public and private meetings. Detailed numbers are given in Table 1.2. Knowledge transfer into the Center has continued through regular meetings with the Center's Industrial Research Board and through seminars and visits from representatives of leading companies, which 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.

Table 1.2. *Center Output in Period 10*

Publications	
Peer Reviewed Journal Publications	24
Submitted for Review	6
Peer Reviewed Conference Proceedings	4
Books and Books Chapters	2
Conference Presentations	27
Other Dissemination Activities	14
Awards and Honors	14
Ph.D. and M.S. Graduates	6
Postdoc Alumni	6
Patents and Patent Disclosures	6

Furthermore, after five highly successful installments of the biennial Berkeley Symposium for Energy Efficient Electronic Systems, the Center for E^3S teamed up this year with the IEEE S3S Conference. Combining the Berkeley Symposium with the IEEE S3S Conference (October 14-17, 2019, in San Jose, CA; http://s3sconference.org) was a natural choice since it covers many of the E^3S topics, and it will ensure that the spirit of the Berkeley Symposium will live on after the Center sunset. Six current and former E^3S senior investigators joined the S3S organization committee this year (**Eli Yablonovitch**, **Tsu-Jae King Liu**, **David Zubia**, **Farnaz Niroui**, **Eugene Fitzgerald**, and **Philip Wong**). We anticipate that the merger of the Berkeley Symposium with the world-renowned IEEE S3S Conference will create the premier gathering event for academia and industry to exchange the latest research results on energy-efficient circuits and devices, 3D Integration, and silicon on insulator technology.

Center Legacy Development Activities in Period 10

The Center considers the development of a lasting, impactful, and self-sustaining Center legacy in both research and education of utmost importance. With input from the E^3S External Advisory Board and the E^3S Industrial Research Board, the leadership team of the Center for E^3S concluded last year that pursuing different paths for the different E^3S research themes is the most successful approach toward the development of strong and lasting legacy programs. The different themes represent different levels of technological maturity, and they will need to evolve separately after incubation in E^3S.

Whereas lasting research and education projects will be supported by grants and industry funding sources (see below for more details), E^3S is working directly with the UC Berkeley College of Engineering to coordinate legacy efforts and establish sustained administrative support. An important step in this direction was the extension of the TTE program to computer science students with a two-year $400,000 grant of the Hopper-Dean Foundation. This grant will also include salary support for a program director.

In addition, the main research legacy of the Center for E^3S, the Berkeley Emerging Technology and Research (BETR) Center has significantly increased its impact and research activities with two more companies (Texas Instruments and Taiwan Semiconductor Manufacturing Company) joining the previous four companies (Applied Materials, Atomera, Lam Research, and Futurewei). Established in 2016, the goal of the BETR Center is to create a hub for physical electronics research at UC Berkeley. The Center is led by E^3S senior investigators **Tsu-Jae King Liu** (*Dean of the College of Engineering, UC Berkeley*) and **Jeffrey Bokor** (*Chair of EE and Assoc. Chair of EECS Department, UC Berkeley*), and managed by **Michael Bartl** (*E^3S Executive Director*), and includes several additional E^3S investigators as members. BETR is an industry-funded research center with the goal to form interactions with companies for long-term research collaborations and knowledge transfer. Corporate sponsors gain early access to innovative ideas and research results, while university researchers gain insight into challenges faced by industry.

Additionally, the Center for E^3S has several self-sustaining research and education initiatives and programs established and/or initiated:

- Negative Capacitance Industry-Supported Center
- Graphene Nanoribbons Multidisciplinary University Research Initiative (MURI)
- Semiconductor Research Corporation (SRC) JUMP Centers
- E^3S e-Book and nanoHUB Website
- Transfer to Excellence REU Renewal Grant and Third-Party Support

Center Management Changes in Period 10

The only major change in E^3S Center Management in period 10 was the departure of Associate Director for Education, **Lea Marlor** (who resumed her graduate studies in engineering education), from the Center and the Executive Committee in April of this year. The Center is delighted to report that an excellent replacement was found in **Nicole McIntyre**, who came to E^3S from UC Berkeley's EECS Department where she was Lead Adviser & Program Coordinator in the Undergraduate Affairs Office. **Nicole McIntyre** started her roles as Associate Director of Education and member of the Executive Committee in the Center for E^3S in May of this year, and successfully managed all summer TTE and RET programs fully independently. The current organizational chart of the Center for E^3S is given in Appendix B.

Summary of Plans for Period 11

Research Plans for Period 11

Entering the final six months of the Center for E^3S, no changes in key personnel (i.e. senior investigators/faculty) and no changes in the current main research directions of the four themes and system integration are planned. Research efforts will be focused on completing current projects according to the Center's strategic research plan and the longer-term Center legacy efforts.

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

- *III-V Nanowire TFETs:* The **del Alamo** group will continue to investigate the VNW geometry to achieve III-V transistors with steep subthreshold characteristics for both MOSFET and TFET structures. In particular, the group will focus on in-situ atomic-layer etching and atomic-layer deposition of the gate dielectric for advanced 3D transistors with the goal of fabricating InAs/GaSb staggered-bandgap vertical nanowire Esaki diodes and tunnel FETs.
- *Chalcogenide TFETs:* The **Kong** group will extend the recently developed direct patterning of the monolayer MoS_2 growth during the synthesis step to other 2D materials. This will provide a facile method for the repeatable direct synthesis of 2D materials for future electronics and optoelectronics. This direct patterning method not only saves the step for lithography and patterning, it also allows the repeated use of the template mask, which leads to cost-effective fabrication in the future. The **Javey** group will further investigate photoluminescence properties of as-exfoliated chalcogenide monolayers under electrostatic doping. In particular, in collaboration with the Bulovic group at MIT, they will examine diffusion properties of excitons and trions by measuring the spatial, temporal and spectral character of the photoluminescence emission under different gate voltages and illumination conditions. With these data in hand, the team expects to gain a comprehensive understanding of the diffusion of different quasi-particles in these monolayers. This will have wide implications in the design of TMDC optoelectronic and electronic devices.
- *Graphene Nanoribbon TFETs:* The **Fischer** group (guided by theoretical input of the **Louie** and **Yablonovitch** groups, and device fabrication by the Bokor group) will continue to explore and expand the rational bottom-up synthesis strategy for graphene nanoribbon (GNR) tunnel junction devices. The **Fischer** group will design and synthesize the next generation of metallic GNRs based on a mirror symmetric monomer precursor. This will have the advantage that the relative orientation of the monomer in the growing polymer chain reliably yields metallic GNRs rather than semiconducting GNRs resulting from monomer misalignment during the polymerization. In collaboration with the **Bokor** group, wet and dry transfer processes of GNRs onto insulating substrates will be continued to enable measurement of the conductance of metallic GNRs in a device setting. Meanwhile, the **Louie** group will further study GNRs with metallic narrow band by first-principles calculations, and investigate the Coulomb repulsion of electrons on the relatively localized orbitals forming the narrow band metallic GNRs. The goal is to prevent the designed structures from developing band gaps, i.e., forming Mott insulators.

Theme II – Nanomechanics: The nanomechanics team consisting of the research groups of **Tsu-Jae King Liu**, **Junqiao Wu**, **Vladimir Stojanović** (all *Berkeley*), **Vladimir Bulović**, **Jeffrey Lang**, **Farnaz Niroui**, **Timothy Swager** (all *MIT*) and **David Zubia** (*UTEP*) will continue work toward demonstrating reliable nano-electromechanical (NEM) switch (or relay) operation below 10 mV using 1) coated body-biased NEM relays, 2) squeezable molecular switches ("squitches"), and 3) stretchable monolayer switches ("stritches").

- *Low-Voltage Relay Design and Integrated Circuit Operation:* Based on recent breakthroughs in ultra-low-voltage operation of NEM-based switches, the **Liu** group, in collaboration with the **Stojanović** group will systematically study the impact of ultra-low-voltage operation (V_{GS} and V_{DS}) on the stability of relay on-state resistance at room temperature. Following the discovery of greatly improved NEM relay characteristics at cryogenic temperatures, the team will also explore operation of relays and integrated circuits at temperatures below 1 Kelvin. The goal is to evaluate their compatibility with milli-Kelvin temperatures required for quantum computing. Meanwhile, the **Wu** group will continue research on exploring NEM relay coatings to minimize contact stiction and thus hysteresis voltage. Focus will be on 2D chalcogenide materials as coatings. In particular, they plan to thoroughly study the deep electron traps in MoS_2-WS_2 layers, including quantify the energy level, the capture cross section, the density, the meta-stability, and the atomic configuration of the related defects.
- *Squitch Project:* The **Squitch** team (the **Bulović**, **Lang**, **Niroui**, and **Swager** groups at *MIT*), in collaboration with the **Liu** group at *Berkeley*, will focus on the development, characterization and use of all-graphene squitches (both two- and four-terminal squitches). The research will focus on four general activities: The first activity is squitch fabrication, specifically four-terminal squitch fabrication. The second activity is to investigate the impact, if any, of electromigration on squitch performance. The use of all-graphene squitches, which cannot exhibit electromigration, is critical to this investigation. The third activity is to demonstrate simple circuits based on squitches, the first of which will be a ring oscillator. The final activity is molecular engineering, namely the search for a molecular layer the yields the greatest current modulation without exhibiting hysteresis (for low-voltage operation) or switching degradation (for long life).
- *Stritch Project*: The inter-institutional **Stritch** team with project leader **David Zubia** (*UTEP*) and the *Berkeley* research groups of **Liu**, **Javey**, and **Wu** will continue to develop MEMS switches based on stretching 2D materials, in particular, transition metal dichalcogenides (TMDCs). With the new actuator designed completed in the current period and device fabrication underway, the main goal of period 11 will be to complete the new stritch device fabrication and achieve >>3000X increase in conductivity upon stretching of the incorporated MoS_2 TMDC layer.

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

- *Digital-to-Digital Optical Link:* The **Wu**, **Yablonovitch**, **Stojanović**, and **Kim**, will built on previous simulation result to work on experimental demonstration of a full optical link. An important requirement will be to have an electrical input and output. At first, the group will concentrate on fabricating an electrically injected waveguide-coupled device. This will be followed by closing the link with a large area photodiode with the same device structure as the nanoLED. Finally, in order to demonstrate a more efficient full link, the team will create a low capacitance photodiode, which may benefit from integrating the device with another material. This can be done by coupling light from the indium phosphide waveguide to a silicon waveguide in order to route to the low capacitance photodiode.
- *Integrating nanoLEDs on Silicon:* The **Kim** group at *MIT*, in close collaboration with the **Wu** and **Yablonovitch** groups at *Berkeley*, will apply their universal technique to transfer epitaxial films of

compound semiconductors to be interfaced with Si CMOS. Based on this technique epitaxial stack for the nanoLED device will first be grown on a graphene coated InP substrate, then transferred to a Si CMOS with a low-index material to help bond and define the waveguide for the nanoLED. The group aims to demonstrate (1) InP buffer layer grown on top of graphene suitable for growing the nanoLED epitaxial stacks, and (2) the feasibility of exfoliating and bonding the epitaxial buffer film on top of a Si substrate. The longer-term goal is to fabricate the antenna-enhance nanoLED on top of the transferred III-V epitaxial film with demonstration of wave-guide coupling.

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

- *Picosecond Magnetic Switching and Integration with CMOS:* The **Bokor** group, in collaboration with the **Salahuddin** and **Stojanović** groups, will built on the significant progress in the current period on miniaturization of the magnetic GdCo dots used for ultrafast switching. The team will focus on the fabrication of a Hall-cross device with the goal to reliably obtain and measure electrical switching results on GdCo nanodots with <50 nm diameter, and thereby determine the scaling behavior of the electrical switching current with dot size. The group will also study ultrafast spin-Hall effect. The plan is to use picosecond electrical pulses to switch ferromagnets directly using a combination of ultrafast heating and demagnetization of the ferromagnet with deterministic switching of the magnetization as it recovers due to the spin injection by spin-Hall effect.
- *Spin-Orbit Torque Switching:* The **Salahuddin** and the **Wang** groups will continue to investigate topological effects for energy efficient computing and spin orbit torque (SOT) switching and energy efficient computing. Regarding the latter, the **Salahuddin** group will start to leverage E^3S work in the last few years on the charge current control of small magnets for energy efficient learning machines (see also *2cv. System Integration*). The **Wang** group plans to study comprehensively the origin of the large SOT found in sputtered WTe_x by varying the thickness of WTe_x, and by low temperature magnetoresistance, and temperature dependent resistance measurements. The size dependent switching behavior (down to 10 nm), ultrafast switching (< 1 ns), multilevel switching, and possible field-free switching will be investigated as well. Furthermore, the group plans to fabricate an asymmetric synthetic ferrimagnet or exchange coupled nanostructure that will enable field-free spin-orbit torque magnetization switching of the free layer in a perpendicular magnetic tunnel junction.
- *Magnetic Tunneling Junction Devices:* Based on the successful demonstration of spin torque transfer (STT) MTJ devices with incorporated ~2 nm $CoFe_2O_4$ nanoparticles, in period 10, the **Khizroev** group plans to build a complete STT-MTJ device capable of multilevel signals in which spin polarized currents are used both for writing and reading. For this, STT-MTJ devices will be built from non-traditional materials, which will be better suited for the proposed 3D configuration. Particular focus will be on (1) extending the three-level 3D nanostructure devices to four and more layers, and (2) using STT to write and GMR/TMR to read back the multilevel signal.

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

- *System Implementation of E^3S Devices:* In period 11, the **Stojanović** group will continue research into system integration of E^3S nanomechanical and nanomagnetic devices. The goal is to explore the opportunity for inherent non-volatility, which may fundamentally alter the balance between computing, communication, and storage for a given application. The goal is to provide both a path to quantifying the benefits of the emerging device technologies at the circuit/system level as well as guidance to the device designers on which device design parameters are critical to improve from the system level perspective. In particular, the group will focus on comparative analysis of the NEMory, ReRAM, and CMOS-based memories for the large multi-headed attention neural net for natural language processing applications, which is ideal for edge-based inference devices.

- *Analog Machines for Digital Optimization:* The **Yablonovitch** group will further explore the use continuous-time analog machines, such as the electrical LC oscillator-based Ising machine developed in the current period, for digital optimization. After demonstrating successful application of their Ising machine by solving a 32-spin problem, the focus in the next period will be on optimization of a much larger class of merit functions beyond the Ising Hamiltonian. The group will use analog ways of performing Lagrange multiplier optimization for applications in control systems, operations research and artificial intelligence.
- *Stochastic Boltzmann Machines:* In period 11, the research plans of the **Salahuddin** group will include stochastic Boltzmann machines—an implementation of the Ising model with stochastic units. This is based on the demonstration that a conventional transistor coupled with a properly designed spin orbit torque (SOT) magnetic tunnel junction (MTJ) device could be used to implement the stochastic units (neurons) needed for the Boltzmann machine [25]. Here the SOT is used to bias the stochastic switching of the magnet, allowing for the 'weighting' of the resistance seen through the MTJ. The group will work on SOT devices to reduce the current needed to deflect magnetization, which will reduce the power consumption while being used as a stochastic neuron.

Education and Diversity Plans for Period 11

Associate Director of Education, **Nicole McIntyre** (*Berkeley*) will remain committed to development and delivery of the continuing education programs. The Education and Diversity efforts will continue to 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.

Education efforts in period 11 will focus on the sunsetting process and finalizing knowledge transfer and education legacy materials. This includes continued development of the Theme I, III, and IV eBooks and publishing of the Center's series of video lectures. Due to the limited funds available during the sunsetting process, the E^3S REU program has concluded after Summer 2019. Additionally, the size of the E^3S Teacher Fellows Program cohort will decrease as we continue to utilize a RET no-cost **extension (**Award Abstract #1405547)**.**

The Transfer-to-Excellence REU program will continue in period 11, as NSF funding was renewed in period 10. Additionally, the program is supported by an NIH grant secured by the UC Berkeley Center for Genomics Editing and Recording (CGER). Period 11 efforts will include continuing to develop the Center's partnership with CGER, securing additional funding to ensure the continued success of TTE REU after the Center sunsets, and continuing to use past evaluation data to improve future offerings.

Knowledge Transfer Plans for Period 11

In period 11, the Center for E^3S will continue its broad set of knowledge transfer activities, both transfer out of the Center and transfer into the Center. In particular, the Center will further extend and strengthen its activities in creating an impactful and lasting legacy while continuing its current broad knowledge transfer program. Main focus will be directed toward further increasing the impact of the Berkeley Emerging Technologies Research (BETR) Center by recruiting new industrial members and extending its research portfolio.

The defining goal for knowledge transfer activities in period 11 of the Center for E^3S will be to further extend and strengthen an impactful and lasting legacy while continuing its current broad knowledge transfer program. On the educational knowledge transfer side, the goal will be to launch the E^3S *nanoHUB.org* website and post educational videos, which will be available to a wide audience from high school to graduate student level. Furthermore, E^3S plans to publish the open-access e-book on energy efficient electronics by the end of period 11.

The Center will also continue to strengthen knowledge transfer from its successful educational and diversity undergraduate programs, in particular, the summer research experience programs for California community college students and faculty, by publishing journal articles and conference proceedings.

II. RESEARCH

1a. *Goals and Objectives*

Since its inception, the goal of the Center for E^3S has been to develop **electronic systems operating at the minimum energy requirement for performing digital functions**. In fact, E^3S was formed with the recognition that the energy used to manipulate a single bit of information is currently ~100,000 times greater than the theoretical limit. Therefore, the central aim of the Center has been to develop an aggressive and disruptive approach to close this gap. Given recent advancements in cloud computing, social networking, mobile Internet and data analytics, and the associated increase of battery powered electronic systems, the development of logic systems that can operate at significantly reduced power consumption is now as relevant as ever.

The Center for E^3S seeks technological breakthroughs for two fundamental components of digital information processing systems: the communications logic switch (transistor) and the short-to-medium range communication of information between logic elements. Research in the Center for E^3S is guided by fundamental considerations and has been pursued by a collaborative approach, involving engineers, chemists, physicists, and materials scientists from five institutions (Berkeley, MIT, Stanford, UTEP, and FIU). Using a four-pronged approach, involving nanoelectronics (theme I), nanomechanics (theme II), nanophotonics (theme III), and nanomagnetics (theme IV), E^3S seeks to develop logic systems operating at switching energies approaching the Landauer limit— the theoretical switching energy limit of $kT\ln(2)$, or about 18 meV at room temperature [26-28].

Current state-of-the-art transistors, for all their success in forging today's interconnected society, are far from reaching the Landauer limit. In fact, leading-edge CMOS technology currently dissipates a minimum of ~10,000 eV of energy per digital function (including the energy required to charge the wires). While the ITRS Roadmap [29] projects this value to be reduced to ~1,000 eV per digital function in the year 2022, this energy value is still orders of magnitude larger than the theoretical limit. One of the reasons is that current transistors are thermally activated and thus lack the sensitivity to operate at low powering voltages (below ~0.7 V), even as their dimensions become smaller and smaller. From its very beginning, E^3S has set an aggressive goal for the proposed new switches with a steepness of ~1mV/decade sub-threshold swings. Figure 2.1 presents a schematic comparison of today's thermally activated conventional transistors versus the desired properties of the new type of switches pursued by E^3S. Switch characteristics are parameterized by sub-threshold swing, *S*, which represents the steepness (or sensitivity) of a switch. Here, the value of 60 mV/decade for the sub-threshold swing is equivalent to the Boltzmann factor, and is typical for thermally activated devices.

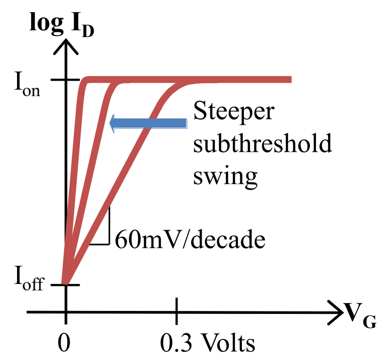

Figure 2.1. Characteristics of current (log scale) vs. voltage (linear scale) of a logic switch. In current transistors the subthreshold swing (S) is limited by the Boltzmann factor to a steepness of $\ln(10)kT/q$ = 60 mV/decade at room temperature.

Center for E^3S researchers recognized early on that new types of transistors, which can operate at significantly lower powering voltage are inevitable in today's quest of creating a fully interconnected and mobile society. In its search for developing a new ultra-low energy switch the Center established several key specifications that this new switch must meet, including steepness, ON/OFF conductance ratio, and current or conductance density. The values for these key specifications, which were set at the start of the Center are given below.

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

The requirement of ~1 mV/decade steepness of the subthreshold swing is necessary to achieve switching at ~7 mV of powering voltage. This is in stark contrast to the ~700 mV needed in conventional, thermally activated transistors to maintain a desired ON/OFF ratio of ~10^6. Such a high ratio (i.e. low leakage current in the OFF-state) is needed since logic transistors are often at rest waiting for a signal. It should be emphasized that electrical noise in circuits is smaller than 1 mV. Therefore, good signal-to-noise ratio can be maintained even while lowering the powering voltage to 7 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 1μm device should conduct at ~1 kΩ in the ON-state) is critical for miniaturization and clock speed. For a small switch to deliver sufficient current to charge the wires in less than a clock period, today's typical requirement is a current density of one milli-Ampere per one μm of transistor size in a one-Volt circuit. Since the goal of the new switch is to lower the voltage well below 1 V, the corresponding switch conductance requirement becomes 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 5)*	Yearly after Period 2	P3: 1 P4: 3 P5: 0
	New joint research funding opportunities *(discontinued after period 5)*	Beginning in Period 3	P3: 1 P4-5: 2
	Publications with authors from multiple institutions	Yearly beginning in Period 3	P3: 1 P4: 2 P5: 4 P6-P10: 5
	New joint research funding awards *(new, as replacement)*	Yearly	P6: 1 P7: 0 P8-P10: 1

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

1c. *Problems Encountered*

A problem faced by E^3S in period 10 was the departure of co-PI and theme III (nanophotonics) investigator, **Constance Chang-Hasnain** (*Berkeley*). The reason for her departure was that she took on new administrative roles at Berkeley (including director of the Marvell Nanofabrication Lab). Since this departure happened at the beginning of the E^3S sun-setting period, the leadership team decided not to consider a replacement senior investigator. Instead, the nanophotonics group will collectively focus on the current research efforts in antenna-enhanced LED design and optical waveguide coupling.

All other problems encountered in period 10 have been mainly at the individual project level and not of magnitude that would require major changes in research direction or at the personnel level.

2a. *Research Thrusts in Period 10*

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

Center Synergy: Of the 17 research projects currently conducted in the Center for E^3S, 88 percent (15) are collaborative projects (i.e. they are joint projects between groups of at least two senior investigator) and more than half of them (9) are multi-institutional, connecting senior investigators from at least two different E^3S institutions. This highlights the collaborative nature across institutional borders in the Center for E^3S.

This collaborative nature of the Center for E^3S has been further exemplified by a special postdoc program established in 2016: The Center for E^3S *inter-institutional postdoc program*. As described in previous annual reports, through this program, each of the four research themes hired an additional postdoctoral researcher into a joint position between at least two E^3S faculty members from different institutions. The *inter-institutional postdoc* was required to spend research time at the different E^3S institutions to increase collaborative projects and publications. While this program ended with the beginning of this period (due to reduced availability of funds, it left a significant lasting impact, exemplified by a notable increase in multi-institutional publications.

E^3S Researchers: The E^3S collaborative research and education programs have continued to bring together research groups from five academic institutions: University of California at Berkeley (UC Berkeley), Massachusetts Institute of Technology (MIT), Stanford University (Stanford), University of Texas at El Paso (UTEP), and Florida International University (FIU). The composition of research groups from these institutions is as follows:

- *UC Berkeley*: Jeffrey Bokor, Felix Fischer, Ali Javey, Tsu-Jae King Liu, Steven Louie, Sayeef Salahuddin, Vladimir Stojanović, Junqiao Wu, Ming C. Wu, and Eli Yablonovitch.
- *MIT*: Vladimir Bulović, Jesus del Alamo, Jeehwan Kim, Jing Kong, Jeffrey Lang, Farnaz Niroui and Timothy Swager
- *Stanford*: Shan Wang
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

The participation of all senior investigators (faculty) within the Center's main research themes is given in the table below. Note that **Vladimir Stojanović** (*Berkeley*) leads the system integration efforts of the Center and collaborates with all four themes.

Table 2.2. Faculty Participation by Theme in Period 10

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

Legend: x* denotes theme leader

The aim of the nanoelectronics theme is to develop a logic switch that is orders-of-magnitude more energy efficient than the conventional transistors. The ultimate goal is a solid-state switch that exhibits high ON/OFF ratios, high conductance (current) densities, and steep modulation, that can be actuated in the ~10 milli-Volt range. For such an ultralow-voltage switching device, E^3S researchers recognized early on that tunnel switches operating by the density-of-states modulation mechanism (also called the "energy filtering mechanism") are needed [2, 3]. However, experimental research failed to yield devices that approach the predicted and hoped-for performance. As was pointed out by E^3S, the main reason for underperformance of current tunnel transistors is that they operate by the tunnel-distance modulation mechanism. While they show good steepness at low current densities [4-7], they are rather ineffective at high conductance (current) density needed for high clock speed. When averaged over both low and high current densities, only a ~50 percent reduction in operating voltage might be achievable, (at best 250 mV), compared to today's conventional transistors.

Guided by theme leader **Eli Yablonovitch** (*Berkeley*), E^3S nanoelectronics researchers elucidated that previous attempts to fabricate density-of-states modulation switches have failed because the density-of-states modulation mechanism demands higher materials interface perfection than ever previously required and achieved in solid-state electronics. The reason for this is that tunneling probability, which is proportional to available two-dimensional density of quantum well states, needs to compete with the corresponding defect 2D density of states—itself a very important figure-of-merit in electronics science. Unfortunately, even in the most favorable material systems (Si/SiO_2 interfaces) [30], after decades of research, the defect density does not fully meet the TFET requirements for good ON/OFF leakage. In response to this important insight, the Center has focused on both searching for new material systems with ultra-low interfacial defect states and to more fully understanding interfacial effects and trap-assisted tunneling.

The **del Alamo** group (*MIT*) uses III-V vertical nanowire TFET structures as model systems [2, 3] to study interfacial effects and trap-assisted tunneling, and other non-idealities of tunnel transistors in collaboration with the **Yablonovitch** group. The goal is to discover the ultimate performance potential of tunnel transistors by performing current-voltage spectroscopy of single trap nanowire tunneling. In addition, **Yablonovitch** is addressing the question of the fundamental spectroscopic sharpness of tunneling energy levels, with the emphasis on the spectral wings, which determine steepness and ON/OFF ratio. Regarding the search for new semiconductor materials with ultra-low interfacial defect states the Center investigates two different systems: Two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs). The **Javey** group at Berkeley and the **Kong** group at MIT develop new bottom-up synthesis methods for 2D-TMDCs, which are single-layer, fully covalently bonded structures with minimum surface roughness and low density of dangling bonds. Semiconducting GNRs, on the other hand, are chemically synthesized by organic chemist **Felix Fischer** (*Berkeley*) in an atom-by-atom fashion. Due to the fully controlled synthesis, the electronic properties of GNRs can be precisely tailored, including quantum tunneling heterostructures with built-in molecular quantum dots. The experimental aspects of this project are supported by theoretical electronic structure calculation by physicist **Steven Louie** and guidance by **Eli Yablonovitch** (both *Berkeley*).

The following provides details of period 10 research efforts in the nanoelectronics theme.

Ia. Vertical Nanowire TFETs

The goal of this project has remained the demonstration of single-channel III-V vertical nanowire TFETs with steep subthreshold characteristics. In recent years, the **del Alamo** group (*MIT*) has shown that vertical nanowire (VNW) III-V TFET structures are excellent model systems to study the underlying physics of tunneling in semiconductors, while revealing the issue of defect assisted tunneling in the OFF-state [3]. The **del Alamo** group has developed very high aspect ratio nanometer-scale etching technology and a new rapid thermal annealing (RTA) step capable of reaching sub-10 nm diameters [2, 14, 15]. In the last period, the group even succeeded in fabricating working InGaAs VNW MOSFETs with nanowire diameter down to 7 nm, the target diameter for which prominent single-channel electron transport is expected [31]. In period 10, the **del Alamo** group carried out detailed studies of excess OFF-state current due to band-to-band tunneling and the floating-body effect in InGaAs FinFETs. These mechanisms affect the subthreshold behavior of all field-effect transistors based on narrow bandgap materials with a floating body, regardless of their structure. As a result, this study is of great relevance for future electronics almost regardless of what path it follows.

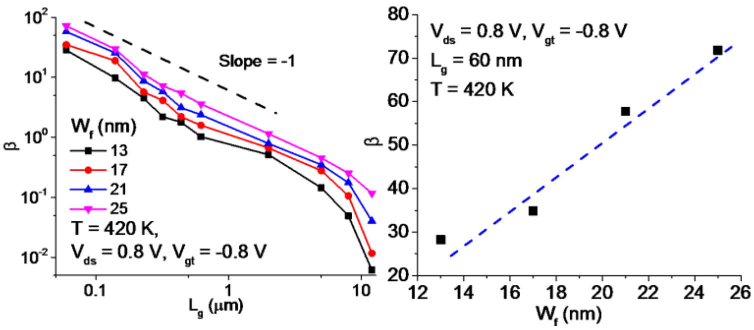

Figure 2.2. Left: Current gain of parasitic bipolar transistor versus gate length for InGaAs FinFETs with different fin width. **Right:** Current gain as a function of fin width for transistor with gate length of 60 nm.

InGaAs FinFETs are challenged by relatively high leakage current in the OFF state, originating from band-to-band tunneling (BTBT) at the drain end of the channel that is amplified by a parasitic bipolar effect (PBE) as a result of its floating body. The **del Alamo** group has developed a simple model of the PBE in InGaAs FinFETs, which captures the key gate length and fin-width dependences (Figure 2.2). The model accounts for surface recombination at the sidewalls of the fin and bulk recombination at the heavily doped source. Compared with experimental results, the model suggests that fin sidewall recombination dominates in long gate length transistors and leads to an exponential gate length dependence of the current gain on the parasitic bipolar junction transistor (BJT). The model enables the extraction of the carrier diffusion length, which exhibits the predicted fin-width dependence. For short gate length transistors, source recombination dominates, and the parasitic bipolar gain scales with the inverse of the gate length. Separately, the group studied the impact of fin-width scaling on transport in highly doped InGaAs fins and the effect of digital etch (DE). These are prototype structures, which exist in virtually all advanced 3D devices. Experiments suggest the existence of a 10-nm-wide “deadzone” on each side of the fin that does not contribute to transport. The extent of the deadzone cannot be mitigated sidewall passivation. An explanation is proposed based on the combination of Fermi-level pinning and mobility degradation as the fin width scales down leading to an apparent wider deadzone than predicted from Fermi-level pinning alone.

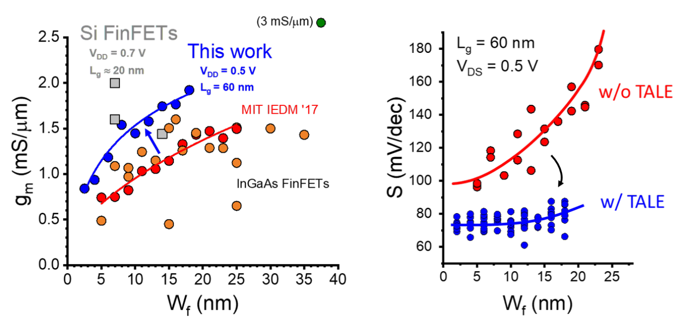

Figure 2.3. Impact of in-situ atomic-layer etching and atomic-layer deposition of gate dielectric in transconductance (left) and minimum subthreshold swing (right) of InGaAs FinFETs.

Finally, the **del Alamo** group has also continued research on the potential of in-situ atomic-layer etching and atomic-layer deposition of the gate dielectric for advanced 3D transistors by carrying out a detailed characterization study of InGaAs FinFETs fabricated by this new technique (Figure 2.3). They found very significant improvements in both the ON- and OFF-state characteristics of highly scaled InGaAs FinFETs when compared with identical devices fabricated in a conventional way. This suggests both a reduction in interface state density that affects the subthreshold swing and a smoothing of the InGaAs surface that enhances electron transport. Our study dramatically illustrates the extraordinary potential of our new technique for all manner of devices in all material systems.

Ib. Layered Chalcogenide TFETs

The E[3]S nanoelectronics theme recognized early on the excellent potential of two-dimensional transition metal dichalcogenides (2D-TMDCs) for TFETs operating on the desired energy filtering mechanism. In principle, 2D-TMDCs have a completely covalently bonded structure, minimum surface roughness, and low density of dangling bonds or surface defects in their monolayers. In fact, the group of **Ali Javey** (*Berkeley*) demonstrated practically functioning TFETs from 2D materials [32]. However, the **Javey** and **Yablonovitch** groups soon realized that a sharp subthreshold swing employing the preferred energy filtering switching scheme requires sharp conduction/valence band edges with very little to no tail states. This can only be achieved by highest quality 2D chalcogenide materials, and as a result, E[3]S 2D chalcogenide research efforts focused on both the development of new synthesis methods for large-area, uniform 2D-TMDCs (led by the group of **Jing Kong** at *MIT*) and the post-synthesis treatment of 2D-TMDC materials to optimize their properties (led by the **Javey** group).

In period 10, the **Kong** group made significant progress in MOCVD growth of large area, single-crystalline monolayers MoS_2 flakes. Figures 2.4a and b show optical microscope and AFM images, respectively, of a MoS_2 flake with ~500 μm size. Figures 2.4c and d depict characterization results of a similar flake using second harmonic generation. The results indicate that almost the entire flake is single crystalline except the lower left corner region where the nucleation of another flake occurred. The group has also investigated the direct patterning of MoS_2 during the synthesis step. This method showed the potential of using the pre-patterned substrates as a master template for the repeated growth of monolayer MoS_2 patterns at a spatial resolution of 2 μm with excellent homogeneity. Extending this patterning method to other 2D materials can provide a facile method for the repeatable direct synthesis of 2D materials for future electronics and optoelectronics. Not only does this direct patterning method remove the need for additional fabrication steps such as lithography and patterning, it also allows the repeated use of the template mask. This should result in cost-effective fabrication of future 2D material systems.

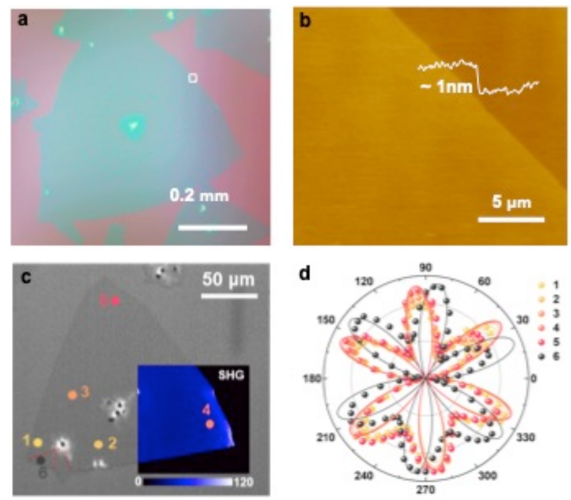

Figure 2.4. a) Optical microscopy image of a large monolayer MoS_2 grown on SiO_2/Si substrate. **b)** AFM image confirming the monolayer nature. **c)** Overlapped second harmonic generation mapping. **d)** Orientation of the second harmonic signal indicates mainly single crystallinity of the flake.

In addition, the **Kong** group has developed MoS_2 based ferroelectric field-effect transistors (FeFETs) in the current period. FeFETs have been considered as a promising electrically switchable nonvolatile data storage element due to their fast switching speed, programmable conductance, and high dynamic range for neuromorphic applications. However, the demonstrated 2D material-based FeFETs, so far, relied mainly on mechanically exfoliated flakes, which are not favorable for large-scale industrial applications, and FeFETs based on organic ferroelectrics typically show a large writing voltage (e.g. $> \pm 20$ V), making this type of memory devices impractical to be commercial viable. The Kong group applied its CVD synthesis method, which is scalable and a manufacturing-compatible process. The group used the MoS_2 as a resistive switching channel for the FeFETs in which the MoS_2 channel is modulated by a hybrid gate stack of HfO_2/ferroelectric $HfZrO_x$ thin films. The programming processes in the 2D MoS_2 FeFETs originate from the ferroelectric polarization switching, yielding two distinct write and erase states for data storage and cumulative channel conductance for artificial synapse applications. The 2D FeFETs display a low-voltage-driven feature ($< \pm 3$ V) and gate-tunable ferroelectric hysteresis characteristics. This work opens an avenue for the use of CVD-grown layered materials as resistive switching media combined with HfO_2-based ferroelectrics for future energy-efficient “brain-on-a-chip” hardware.

The group of **Ali Javey** has focused on 2D material engineering in order to realize better device performance through material quality improvements. In recent years, several breakthroughs were achieved, including a superacid treatment method that “heals” defects in 2D chalcogenides [33, 34], and using photoluminescence lifetime and quantum yield efficiency to fully characterize and understand edge-recombination in 2D chalcogenide materials [35]. From these results, the **Javey** group, in collaboration with the **Yablonovitch** group, developed a method to increase the photoluminescence quantum yield of as-exfoliated MoS_2 and WS_2 monolayers to near unity by electrostatic doping, without any chemical treatment [16]. Remarkably, this work demonstrated that, even in the presence of defects in sulfur-based TMDCs, neutral exciton recombination could be entirely radiative. This result is also of great importance for the E^3S nanophotonics research, in particular for the development of electrically excited antenna enhanced nanoLED with 2D chalcogenide materials as the light emitting source.

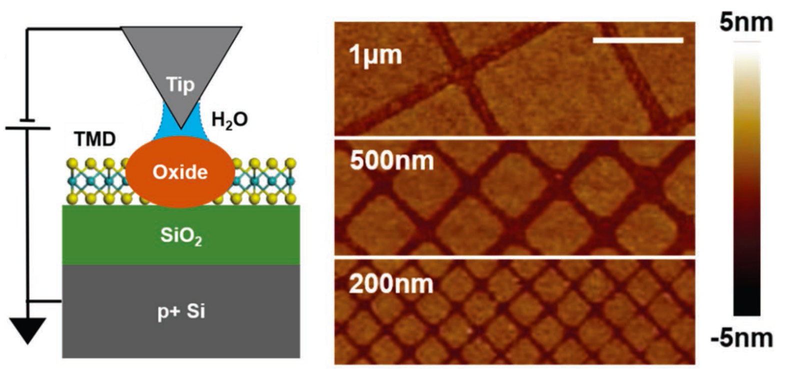

Figure 2.5. Left: Schematic of the scanning probe lithography patterning of a TMDC monolayer, depicting the formation of a water bridge between the tip and the monolayer. **Right:** Atomic force microscopy images of patterned monolayers. Scale bar represents 500 nm.

In this period, the **Javey** group also succeeded in directly patterning monolayer TMDCs without the use of a sacrificial resist [17]. Using scanning probe lithography, a negatively biased tip was brought close to the TMDC surface. By inducing a water bridge between the tip and the monolayer surface (Figure 2.5 left), controllable oxidation is achieved at the sub-100 nm resolution. The oxidized flake is then submerged into water for selective oxide removal, which leads to controllable patterning (Figure 2.5 right). In addition, by changing the oxidation time, thickness tunable patterning of multilayer TMDCs is demonstrated. This resist-less process results in exposed edges, overcoming a barrier in traditional resist-based lithography and dry etch where polymeric byproduct layers are often formed at the edges. By patterning monolayers into geometric patterns of different dimensions and measuring the effective carrier lifetime, the non-radiative recombination velocity due to edge defects is extracted. Using this patterning technique, it is shown that selenide TMDs exhibit lower edge recombination velocity as compared to sulfide TMDs. The utility of scanning probe lithography towards patterning TMDCs and understanding material-dependent properties is of profound interest for nanoscale electronics and optoelectronics.

Ic. Graphene Nanoribbon Quantum Tunneling Structures

The graphene nanoribbon (GNR) project started in period 5, and since then has made tremendous progress in synthesizing novel materials systems capable of producing the most perfect molecular scale device structures—a pre-requisite for future progress in ultra-low voltage switching. GNRs are top-down synthesized polymeric structures that promise atomic precision and low defect density. In addition, GNRs are semiconductors, which distinctly differentiates them from graphene itself, which is a semimetal. The semiconducting property arises from lateral electron quantum-confinement effects in the one-dimensional nanoribbon structure. In period 10, the group of organic chemist **Felix Fischer** has continued to lead the experimental aspects of this project. Broad theory support is provided by **Eli Yablonovitch** and the group of theoretical physicist **Steven Louie**, who has extensive expertise in *ab initio* calculations of electronic

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structures for the design of future semiconductors. In addition, the group of **Jeffrey Bokor** is working closely with this team and provides guidance in integrating GNRs into FET device architectures.

In this period, the **Fischer** group, in close collaboration and with theoretical support by the **Louie** group, has successfully demonstrated that symmetry protected topological states can be rationally engineered into GNRs featuring a metallic band structure. They showed that symmetric placement of half-occupied zero-mode states in a 1D superlattice gives rise to extended metallic bands embedded in an otherwise insulating GNR backbone (Figures 2.6 and 2.7). The key innovation was the use of molecular precursors that each provided a single localized zero-mode state due to an imbalance in the bipartite lattice of the underlying graphene (zero-mode states occur at E = 0 due to symmetry). The team further demonstrated that the resulting 1D metallic bandwidth could be tuned over a large energy range (from 20 meV to 500 meV) through deliberate sublattice symmetry breaking via a thermally activated pentagonal ring closure. This work points to a new strategy for realizing not only 1D metallicity, but also 1D magnetism and other highly correlated 1D phenomena that may arise from a tunable 1D density of states at the Fermi energy (EF). This technology also represents a new strategy to access unusually sharp energy levels ($\Delta E \sim 5$ meV). Such sharp energy levels were recently identified by the **Yablonovitch** group as critical to the successful realization of TFET architectures.

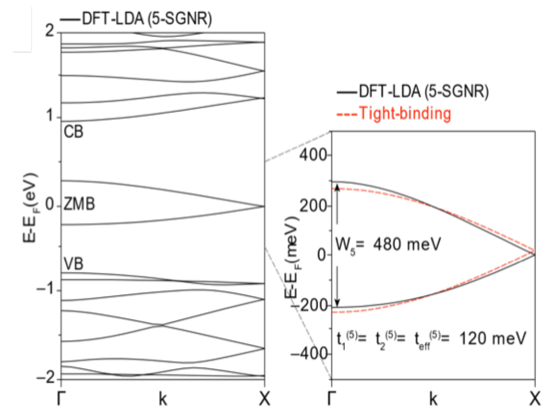

Figure 2.6. Calculated band structure for a GNR with a metallic band structure.

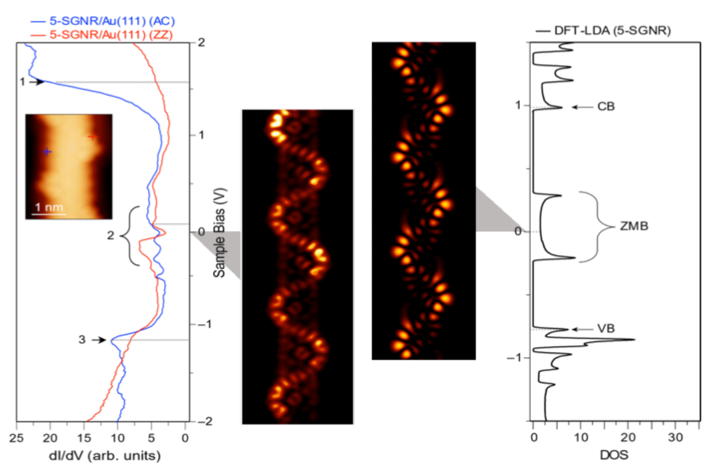

Figure 2.7. Experimental (left) and calculated (right) dI/dV spectra and maps of a metallic GNR.

The **Louie** group showed previously that GNRs possess distinct symmetry-protected topological phases [36]. Furthermore, they have discovered that a wide range of GNRs, including the armchair, cove-edged, and chevron GNRs, have been shown to host rich electronic topological phases depending on their width, edge shape and end terminations [36-38]. In this period, the **Louie** group revealed through first-principles calculations that by applying an experimentally accessible transverse electric field, certain designer GNRs develop tunable topological phases. By applying a periodic spatially varying field, junctions of GNRs between distinct topological phases can be created, with localized topological interface states emerging at these junctions. For example, they found that a boron and nitrogen dimer co-doped armchair GNR with the number of carbon atoms N=11 in the width direction exhibits such tunable topological phases. These discoveries provide design principles for tunable topological flat bands in GNRs using transverse electric fields forming such superlattices. By modifying the profile of the transverse electric field applied on the GNR, the bandwidth and metallicity of the GNR superlattice may be tuned, so that it may be used as building blocks for low-energy consumption tunnel field-effect transistors.

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

Guided by theme leader **Tsu-Jae King Liu** (*Berkeley*), nanomechanics and system integration researchers at E^{3}S have make significant progress in improving NEM switch characteristics and overcome some of the main challenges. For example, the team has shown that circuit design co-optimization to minimize the number of mechanical switching delays per function can compensate for the inherently slow switching speed of mechanical relays [39]. A further challenge for NEM switches is contact stiction, which 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 (Figure 2.8) E^{3}S researchers have developed several new approaches to avoid contact stiction, including a new body-biased relay design with smaller total electrode contact area [40], the "squitch" concept (invented at *MIT*) in which a molecular layer is sandwiched between the two conductive electrodes to prevent direct contact, and a complementary "stritch" concept (invented at *UTEP*), which uses electrostatic force to stretch a two-dimensional molecular layer suspended between the two conductive electrodes, in order to induce a phase change and thereby modulate the current. The "squitch" project has been pursued by the *MIT* groups of **Vladimir Bulović**, **Jeffrey Lang** and **Timothy Swager** in collaboration with the groups of **Tsu-Jae King Liu**, **Junqiao Wu**, and **Vladimir Stojanović** at *Berkeley*. The Berkeley group has been responsible for the new relay design and antistriction coating progress, yielding sub-50 mV switching. In addition, the **Liu** group collaborates with the group of **David Zubia** at *UTEP* to fabricate MEM actuators for the "stritch" project.

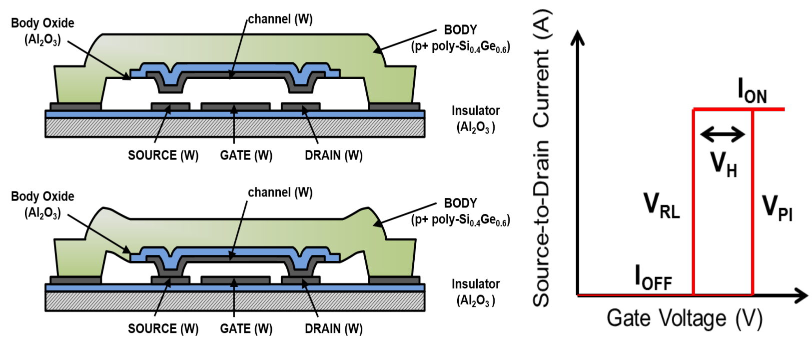

Figure 2.8. Left: Schematic illustration (cross-sectional view) of a NEM switch in the OFF state (upper) and in the ON state (lower). **Right:** Corresponding current-voltage plot, showing pull-in voltage (V_{PI}), release voltage (V_{RL}) and hysteresis voltage (V_H).

The following provides details of period 10 research efforts in the nanomechanics theme.

IIa. Ultra-Low-Voltage Relay Design and Operation

Under the guidance of theme leader **Tsu-Jae King Liu**, research efforts continued to focus on further improvements of the NEM relay design and low-voltage operation. In period 10, the team made an important discovery: It was found that relays can be operated even more reliably, with sub-25 mV voltage signals, at temperatures below 100 K. This is the result of a dramatic reduction in hysteretic switching behavior and elimination of contact oxidation at cryogenic temperatures. In more detail, fabricated MEM

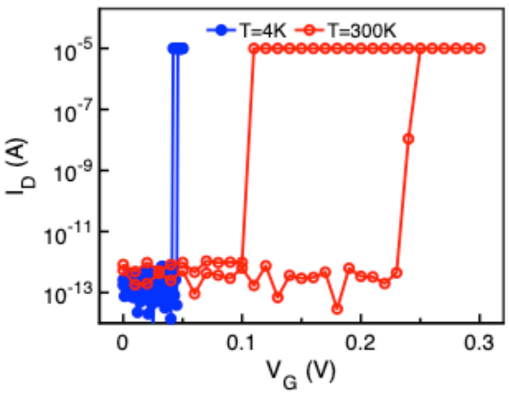

Figure 2.9. Measured relay drain current vs. gate voltage (I_D-V_G) characteristics at 300 K and 4 K, under 1 μTorr pressure. The gate voltage step size is 10 mV for 300 K, and 1 mV for 4 K. The current compliance limit was set to 10 μA.

relay devices and integrated circuits were tested in a vacuum chamber at temperatures ranging from 4 K to 300 K. Relay transfer characteristics measured at 300 K and 4 K are shown in Figure 2.9. It can be seen that the relay switches on and off abruptly with sweeping gate voltage, and that an applied body bias allows for low gate voltage operation. The hysteresis voltage is only 4 mV at 4 K, indicating that MEM relay circuits potentially can be operated with sub-10 mV voltage signals. It should be emphasized that this result is approximately two orders of magnitude lower than for MOSFETs.

Following this exciting discovery, the **Liu** group conducted a systematic study of relay characteristics at cryogenic conditions. The measured temperature dependences of the turn-on voltage V_{ON} and the hysteresis voltage V_H for MEM relays revealed a slight increase in V_{ON} with decreasing temperature, which can be explained by an increase in structural stiffness (i.e. an increase in the Young's modulus of the poly-SiGe structural material, with decreasing temperature). Interestingly, the hysteresis voltage decreases dramatically with decreasing temperature, indicating that the contact adhesive force diminishes with decreasing temperature, consistent with previous studies [41].

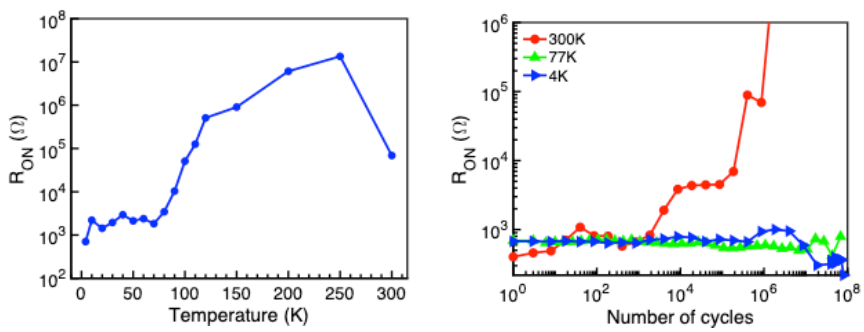

Figure 2.10. Left: Measured temperature dependence of R_{ON}. R_{ON} is fairly stable at temperatures below 90 K, and increases sharply when the temperature increases above 90 K, the boiling point of oxygen gas. At 300 K it is likely that the native oxide formed on the surface of the W electrodes broke down during the DC switching measurement, causing R_{ON} to be diminished. **Right:** Stability of R_{ON} over many on/off switching cycles with 5 kHz square-wave gate voltage signals, measured at 4 K, 77 K, and 300 K.

Another important relay feature is contact oxidation since relays used for implementing digital logic must operate properly over many switching cycles to be of practical use. Previous studies showed that contact oxidation is indeed the primary reliability issue for MEM relays, causing the on-state resistance R_{ON} to increase dramatically over the lifetime of the device [42]. The left panel of Figure 2.10a shows how R_{ON} depends on temperature, increasing significantly for temperatures above 90 K. Since 90 K is the boiling point of oxygen gas (O_2), sub-90 K operation inhibits the formation of native oxide on the electrode surfaces and thereby allows low R_{ON} to be maintained. The right panel of Figure 2.10b compares how R_{ON} evolves over many ON/OFF switching cycles using 5 kHz square-wave gate voltage signals with 2 V gate overdrive and V_{DS} = 0.5 V, at various temperatures. Considering that R_{ON} should not exceed 10 k□ for acceptable relay-based integrated circuit performance [43], the (hot) switching endurance of a MEM relay operating at 300 K is roughly 10^6 cycles. For relays operated at liquid nitrogen temperature (77 K) or liquid helium temperature (4 K), however, the endurance of a relay exceeds 10^8 cycles, since there is no O_2 to oxidize the tungsten (W) electrodes.

Lastly, changes in electrical conductivity of the electrode materials were gauged by sheet resistance measurements of the contacting electrode layer (60 nm-thick W) and the structural gate electrode layer (1.9 μm-thick p-type poly-SiGe), as shown in Figure 2.11. The poly-SiGe does not show dopant freeze-out effects down to 1.8 K, and the resistance of W also remains low down to 1.8 K, indicating that the MEM relays can operate at temperatures as low as 1.8 K.

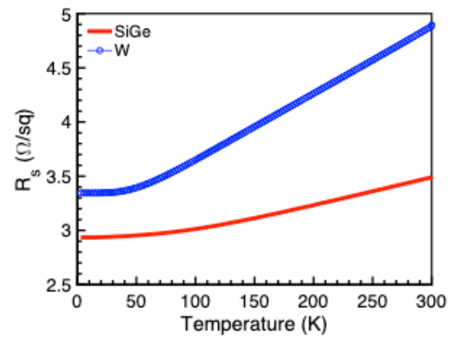

Figure 2.11. Measured dependence of sheet resistance for the W electrode layer and poly-SiGe structural layer.

The demonstration of successful relay operation at temperatures down to 4 K makes MEM relay ICs advantageous for implementation of digital logic with ultra-low power dissipation for cryogenic applications such as quantum computing.

The group of **Junqiao Wu** (*Berkeley*) continued the collaborative work with the **Liu** group in using molecular layers to further reduce surface adhesion of NEM switches without degrading their conduction. To overcome the trade-off between adhesion and conduction, they discovered that single-chain molecules are not able to offer the optimal performance. Recently, the team used self-assembled molecular coatings with branched tails to break the trade-off between adhesion and conduction. In this way, the molecule length can be kept short to preserve conduction. At the same time, the density of fluorine atoms is increased by adding more branches to the molecule, thereby reducing adhesion. The best results were obtained by the branched self-assembled molecular coating perfluoro(2,3-dimethylbutan-2-ol) with 24 fluorine atoms per nanometer. This perfluoro molecule is <0.5 nm long and as such does not degrade conduction substantially. By using this perfluoro coating, a 62 percent reduction in hysteresis and 52 percent reduction in average switching slope was achieved, while the instantaneous switching slope was not greatly affected.

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

The **Liu** group in collaboration with the group of **Vladimir Stojanović** (*Berkeley*) has continued research into demonstrating reliable operation of relay-based digital integrated circuits (ICs) at voltages below 100 mV. The goal remains to prove their suitability for ultra-low active power consumption as well as zero static power consumption. 50-mV operation of digital ICs at room temperature was demonstrated for the first time, enabled by an improved relay design and self-assembled molecular coating to provide for lower contact adhesion to reduce hysteretic switching behavior.

In addition, tremendous improvement of relay-based digital IC characteristics was achieved under cryogenic conditions. Operation of a 2:1 relay-based multiplexer integrated circuit at 300 K and at 77 K is shown in Figure 2.12. Note that the upper relay has positive body bias (V_{BP}) so that it turns on when the select voltage signal (V_{SEL}) is low, while the lower relay has negative body bias (V_{BN}) so that it turns on in a complementary manner when V_{SEL} is high. Thus the upper relay will pass the voltage signal V_A to the output (i.e., $V_{OUT} = V_A$) when V_{SEL} is low (logic '0'), and the lower relay will pass the voltage signal V_B to the output (i.e., $V_{OUT} = V_B$) when V_{SEL} is high (logic '1'). The waveforms in Figure 2.12c show proper circuit operation at 300 K with 100 mV signals, while the waveforms in Figure 2.12d show proper circuit operation at 77 K with < 25 mV signals, made possible by smaller V_H values. It should be noted that V_{OUT} was monitored by an oscilloscope with an internal impedance of 1 MΩ. If a relay has high on-state resistance (R_{ON}) – due to electrode surface oxide formation – the input voltage signal will not be fully passed to V_{OUT} due to the voltage divider effect.

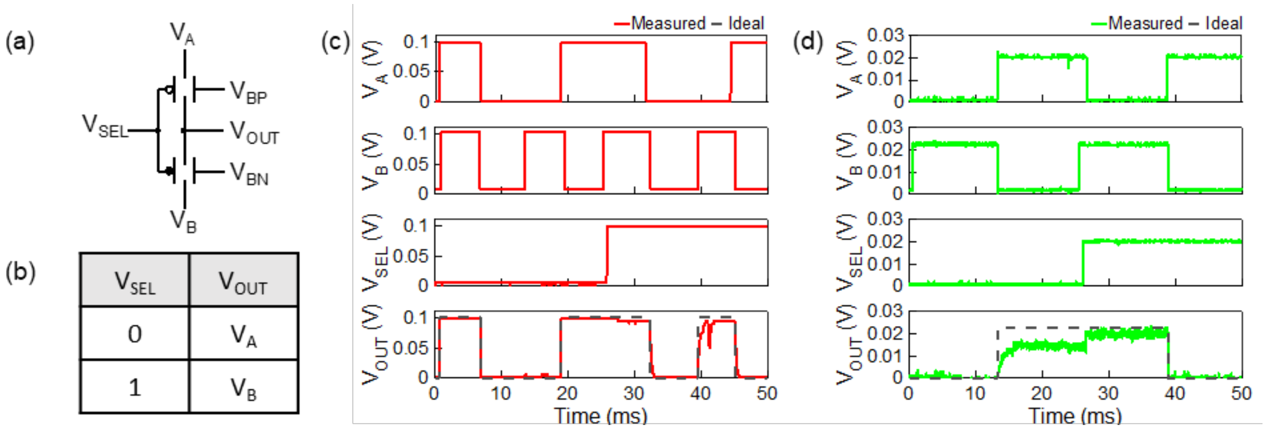

Figure 2.12. Demonstration of ultra-low-voltage operation of a 2-to-1 multiplexer integrated circuit: (a) schematic circuit diagram and (b) truth table; measured voltage waveforms (c) at 300 K (V_{BP}=15.5 V, V_{BN}=-14.6 V) and (d) at 77 K (V_{BP}=17.07 V, V_{BN}=-14.71 V).

IIc. Squitch: Molecular Squeeze-Switch

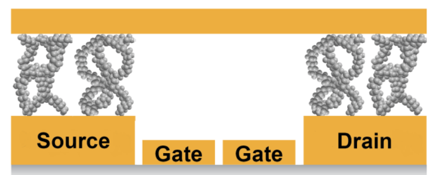

Figure 2.13. Graphic illustration of a four-terminal NEM switch employing a molecular monolayer to define and support its tunneling gap ("squitch").

The research groups of **Vladimir Bulović**, **Jeffrey Lang** and **Timothy Swager** (all *MIT*), in collaboration with the **Liu** group at *Berkeley*, have continued development of a NEM switch designed to conduct via tunneling through an electromechanically compressed gap containing "squeezable" molecules [9]. This "squeezable" switch was invented under E^3S and has also been termed "squitch". An illustrative four-terminal squitch is shown in Figure 2.13, and is labeled as per an equivalent MOSFET. In this switch, a vertically movable conductor is supported by a molecular monolayer that is compressed upon application of a gate-gate voltage, thereby permitting source-conductor-drain electron tunneling. The split gate is recessed to prevent gate-conductor tunneling. Note that the drain/source-conductor gap separation is only several nanometers.

In previous periods, research efforts in the **Squitch** group focused on the development of process steps and flows for the fabrication of squitch tunneling gaps having nanoscale smoothness, planarity and dimensional precision with high yield [44]. In this period, the team continued work on improving squitch yield and performance. Additionally, the work on using two-terminal squitches to investigate the mechanical behavior of the molecular films as they cyclically compress and elongate during switching, has been continued. Finally, in this period, the team has studied graphene-based two-terminal squitches as part of an investigation of the impact, if any, that electromigration has on squitch performance. Recent squitch research outcomes are described in more detail in the following sections.

During the squitch fabrication process, dielectrophoretic trapping of the suspended vertically moving squitch conductor, usually a gold nanorod, has been identified as the yield-limiting process step. For example, gold nanorods tend to agglomerate in suspension, and this agglomeration carries over during trapping. Another issue is that gold nanorods only bond weakly to the molecular monolayer. Therefore, as the dielectropheresis solution dries, its receding edge can carry a nanorod off its underlying electrodes. The team found that this could be overcome by diluting the nanorods in solution. The use of 1:1 water:ethanol to form the dielectropheresis solution, and the use of carbon nanotubes as the suspended conductor all improve yield. These modifications are now in use.

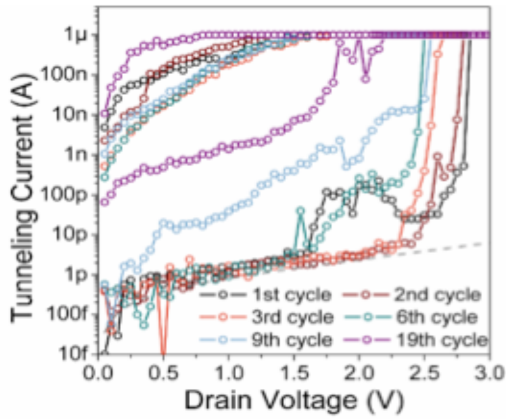

Figure 2.14. Tunneling current in a two-terminal squitch (with a gold nanorod supported by a PEG-thiol layer) as a function of voltage over six different switching cycles.

An important characteristic often observed in squitch switching is a slow upwards drift in current for a given voltage as the switching cycle count increases, as shown in Figure 2.14. During its initial switching cycles the squitch exhibits pA-level off-state currents until it switches on near 2.5 V. However, by the 19th switching cycle, the squitch exhibits nA-level off-state currents before switching on. The group hypothesized that this current drift is the result of either a permanent compression of the molecule layer in the tunneling gap, or perhaps a parting of the layer. Both phenomena would result in a reduced off-state tunneling gap, and hence an increased off-state tunneling current such as observed in Figure 2.14. To quantify the hypothesis, the off-state currents are converted to an equivalent off-state tunneling gap, showing indeed a plausible drop in the tunneling gap as switching proceeds.

In an effort to determine whether the molecular layer did permanently compress and/or part during repeated switch cycling, a cross-sectioned squitch was examined with transmission electron microscopy. During these studies, the team found evidence of a small filament or bump of gold on the lower electrode that should not have been present after fabrication. It is possible that the filament was formed during trapping. However, it is also possible that the filament was formed through gold electromigration from the lower electrode into the tunneling gap, and that the filament (or filaments like it) is responsible for the degradation of squitch performance during repeated use. To investigate this possibility, the team studied the dependence of squitch performance degradation on the combination of cycle count and the on-time duration of each switching cycle. As a byproduct of the investigation into electromigration, it was also observed that the bottom squitch electrodes occasionally exhibited rough edges that caused squitch failure in the form of permanent shorts. These rough edges were traced to damage caused by electrostatic discharge during electrode peeling. This, in turn, led to the development of water-based peeling, which eliminated the discharge and subsequent electrode damage. This form of peeling is now in use.

Another possible avenue to eliminate electromigration is the use of electrodes, which cannot support this phenomenon, such as graphene electrodes. Correspondingly, the team developed an all-graphene two-terminal squitch fabrication process flow, which uses many of the fabrication process steps already developed for the previous fabrication process. As a precursor to an all-graphene squitch, Figure 2.15 (left) shows the active elements of a partially-graphene two-terminal squitch similar to those used by the team in the past. In the new squitch design, the vertically moving top electrode is fabricated from graphene. Further, the graphene electrodes in all squitches are transferred together in one aligned fabrication process step, resulting in a fabrication yield of this squitch design as high as 80%. Squitches of this type with a PEG molecular layer have been recently successfully fabricated and characterized (Figure 2.15, right).

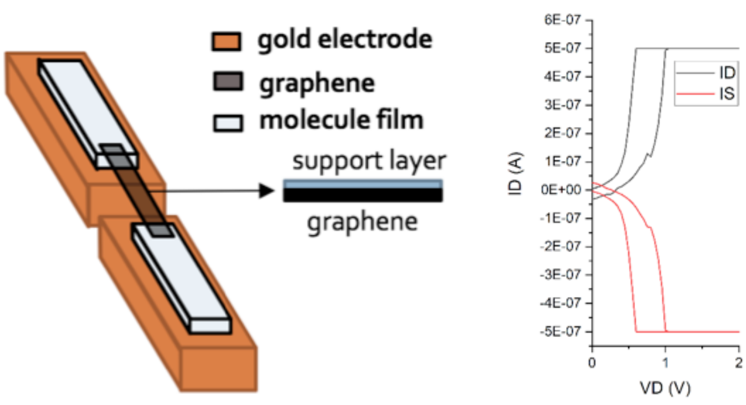

Figure 2.15. Left: Two-terminal squitch with a vertically moving graphene top electrode. **Right:** The drain and source currents of a partially-graphene two-terminal squitch as a function of the drain-source voltage. The power supply current limit is set to 0.5 μA.

Interestingly, the large-signal turn-on voltage in Figure 2.15 (right) is below 1 V, which is lower than typically observed in earlier squitches.

In this period, the **Squitch** team has also investigated the behavior of squitches fabricated with different self-assembling molecular layers. The objective of this investigation is to determine whether molecular engineering is a viable approach to improving and ultimately tuning squitch performance. To date, the behavior of two-terminal squitches fabricated with molecular layers based on the four different molecules has been examined (Figure 2.16). These molecules are all designed to be approximately 3 nm long in their relaxed state. Note that all molecules are terminated with a thiol (SH) group so as to self-assemble onto gold bottom electrodes. Of the four, TDMB and DTDMB are believed to result in the softest molecular layer, while DDT is believed to result in the stiffest molecular layer. Figure 2.17 shows squitch current as a function of squitch voltage for four squitches, each fabricated with a different molecule from Figure 2.16. There is a substantial difference in the nature of the four data sets. For example, the stiff DDT molecular layer exhibits very little, if any, compression as viewed through squitch current, while the much softer TDMB and DTDMB molecular layers exhibit considerable mechanical compression.

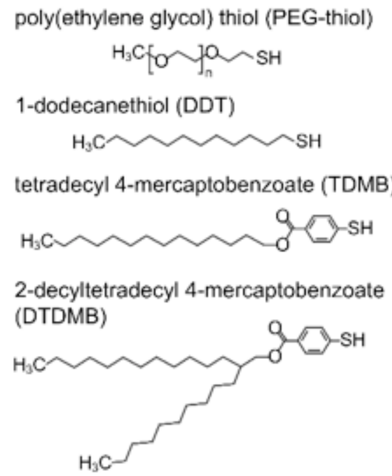

Figure 2.16. Names and chemical structures of the four molecules used to date in squitch fabrication.

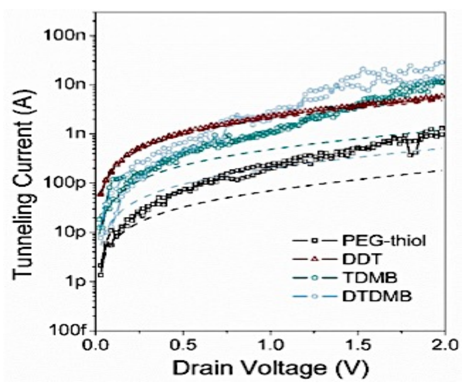

Figure 2.17. Squitch current as a function of voltage for four different two-terminal squitches, each fabricated with a different molecule from Figure 2.16. Dashed lines show the current that should be observed if the molecular layer did not compress. Molecular compression is indicated when the measured data lies above the corresponding dashed line.

Figure 2.18 shows data similar to that shown in Figure 2.14 (i.e. squitch current as a function of squitch voltage for two-terminal squitches displayed over many excitation cycles). Collectively, they show data for squitches fabricated with molecular layers based on all molecules from Figure 2.16. Of particular interest is the rate of squitch performance degradation. For example, the squitch in Figure 2.14, which employs PEG, shows little switching after 19 cycles, whereas all three squitches in Figure 2.18 show considerable switching after 100 cycles. Based on these results it is apparent that the selection of the molecular layer is critical to the performance of a squitch. As a result, the team will continue to pursue molecular engineering as an important component.

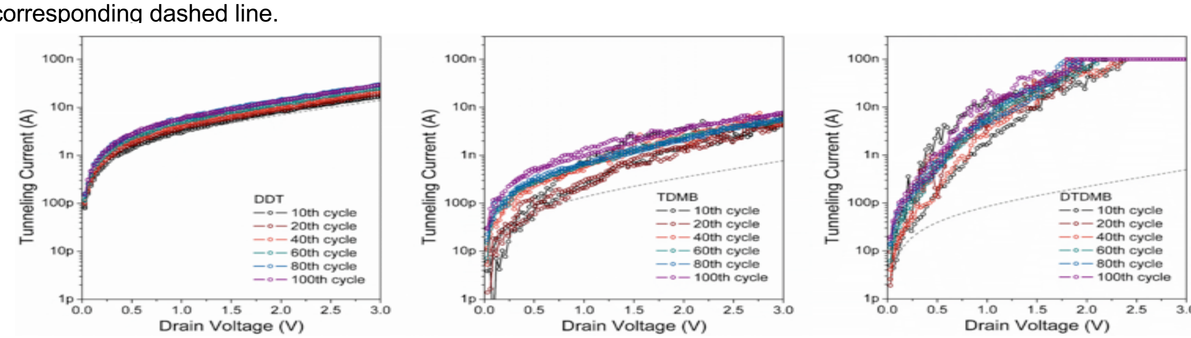

Figure 2.18. Squitch current as a function of voltage for three two-terminal squitches displayed over many excitation cycles. Each squitch is fabricated with a molecular layer based on a different molecule (Figure 2.16).

IId. Stritch: 2D Chalcogenide Stretch-Switch

The Stritch project has continued to be led by **David Zubia**'s group (*UTEP*) in close collaboration with the **Liu** and **Javey** groups (both *Berkeley*). The "stritch" concept is a "stretchable switch" that makes use of the change in bandgap and conductivity of 2D chalcogenide semiconductor layers upon stretching [45]. In past periods, significant progress was made in proof-of-concept experiments. In fact, in the last period, a comb-drive MEMS actuator design was fabricated and 2D-TMDC samples were strained. The group demonstrated a 3000-fold increase in conductivity in MoS_2 flakes stretched to a record 3% strain (Figure 2.19 left) [46, 47]. Theoretical analysis of the stritch device implemented as an inverting circuit showed significant voltage gain derived from strain due to the deformation potential.

In period 10, the **Zubia** group redesigned the actuator to account for previous issues, including vertical actuation, which limited the strain to a maximum of 3%. To switch to the preferred horizontal actuation mode, a simplified MEMS actuator was designed. In addition, the new actuator was also designed to be scalable in size and with the capability to obtain electrical and optical measurements simultaneously. The new actuator design is shown in Figure 2.19 (center) on an SOI substrate. It consists of a thin and long movable beam anchored at opposite ends (sources). Actuation of the beam is achieved by applying a voltage to the gate with respect to the source terminals, (V_{GS}). A MoS_2 flake is clamped across the drain and center of the beam and then stretched when V_{GS} is applied.

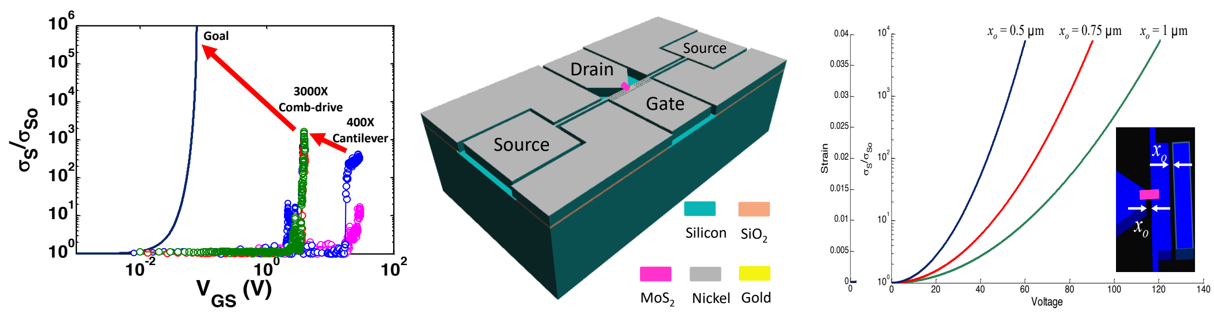

Figure 2.19. Left: Conductivity of 2D MoS_2 increased 3000 times by straining to 3% with a SiGe MEMS actuator. **Center:** Design of new MEMS actuator on SOI substrate. **Right:** Predicted strain and σ_S/σ_{So} vs. V_{GS} characteristics using an analytical model of the device.

The actuator was designed and simulated in the *Coventor* MEMS simulation software and modeled using analytical equations. Modal analyses of the actuator beam predicted a 300 kHz resonant frequency without the MoS_2 flake attached. Figure 2.19 (right) shows output (strain and σ_S/σ_{So}) versus V_{GS} characteristics of the device. The operating voltage decreases as the characteristic length, x_o, of the device is reduced. Although the operating voltage is large, it will decrease substantially as patterning technology at UTEP's nanofabrication facility is developed and x_o is reduced to a few nanometers without having to redesign the whole device. The current fabrication process using a new mask consists of the following steps: (1) patterned photoresist, (2) nickel deposition and liftoff, (3) deep reactive ion etching (DRIE) of top silicon device layer, (4) transfer and clamping of TMDC onto MEMS, and (5) device release. The DRIE etching was performed in the lab of **Jose Mireles** at the *Universidad Autonoma de Ciudad Juarez*, who functions as an external collaborator.

The goal of the nanophotonics theme is to develop highly efficient on-chip optical communication approaching the quantum limit of photons-per-bit in a data-link. E^3S researchers explore new optical materials, develop new nanofabrication methods for optical components, and integrate components into energy-efficient on-chip systems to significantly reduce the photons-per-bit rate from currently used ~20,000 photons to just a few hundreds of photons. Key challenges are to miniaturize novel, ultra-efficient optical components (photoemitters and photoreceivers) to be comparable to the size of transistors, and to connect these components with waveguides at unprecedented coupling efficiencies into integrated systems. These challenges are addressed by the E^3S nanophotonics team in a collaborative approach, including **Ming Wu** (theme leader), **Eli Yablonovitch**, **Vladimir Stojanović** (all *Berkeley*), and **Jeehwan Kim** (*MIT*).

Central to the Center's nanophotonics research endeavors has been to demonstrate the enormous potential of antenna enhancement on optical components with the goal of replacing the laser—the ubiquitous light source in optical communications today [11, 18]—with light emitting diodes (LEDs). Antenna-coupled high-speed nano-LEDs are great candidates for energy-efficient, fast and small optical emitters for on-chip optical interconnects. A breakthrough result by E^3S researchers was the demonstration of spontaneous emission enhancements in antenna-couple nanoLEDs (Figure 2.20) of more than 300 times under optical excitation [19] and more than 200 times under **electrical excitation**—more than doubling previously reported enhancements [48]. These results make spontaneous emission from antenna-enhanced nanoLEDs competitive with stimulated emission in lasers.

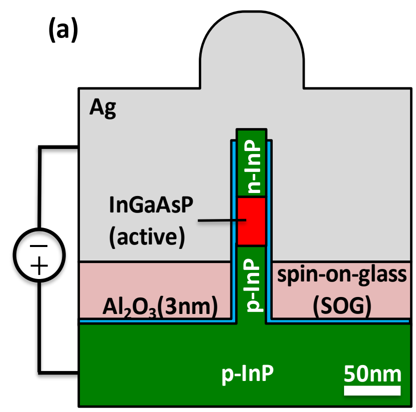

Figure 2.20. Cross-sectional schematic of an electrically injected InP/InGaAsP nanoLED ridge coupled to a cavity backed slot antenna.

Similar enhancement strategies are also considered at the photoreceiver end. In general, the Center laid out a clear strategy toward a more sensitive photoreceiver: (1) A cavity enhanced photo-diode, (2) a very large feedback resistor on the initial trans-impedance amplifier (compensated by high-pass frequency response in the succeeding amplifier stages), and (3) multiple serial-to-parallel slicers that split the load on the parallel slow comparators, which decide whether the bit is 1 or 0.

A third challenge addressed at E^3S is the efficient coupling of nanoscale optical components (photoemitters and photoreceivers) to waveguides, which is of utmost importance for the development of on-chip integrated photonic links. To achieve this, the E^3S nanophotonics research groups of **Eli Yablonovitch** and **Ming Wu**, in collaboration with **Vladimir Stojanović**, uses unique electromagnetic design techniques to engineer and optimize coupling efficiencies of nanoLEDs to single mode optical waveguides. **Jeehwan Kim** (*MIT*) continues to lead the nanoLED growth project in close collaboration with the **Wu** group.

The following provides details of period 10 research efforts in the nanophotonics theme.

IIIa. Antenna-Enhanced III-V nanoLEDs

The **Wu** and **Yablonovitch** groups at Berkeley have continued to investigate and optimize the efficiency and direct modulation rate of the III-V antenna-LED developed at E^3S [18, 19]. In particular, the team has explored the fundamental limits of antenna enhanced spontaneous emission rate in comparison to the rate of stimulated emission of a laser. Laser saturation is a well-known phenomenon [49]. In continuous wave (cw) operation, saturation occurs when the laser optical power saturates with increasing current above threshold. There are several mechanisms that can cause laser saturation, but the most fundamental is known as gain saturation where stimulated emission events occur faster than the device's excited states can be replenished. It can be shown, by several approaches, that the stimulated emission lifetime of a GaAs laser at saturation is given by,

$$\frac{1}{\tau_{stim}} = \frac{c}{n} \times \left(\frac{\text{threshold gain}}{\text{threshold carrier concentration}}\right) \times (\text{saturation photon density}) \qquad \textit{Eq. 2.1}$$

Upon inserting experimentally relevant data, Eq. 2.1 becomes

$$\frac{1}{\tau_{stim}} \approx \frac{3\times10^{10}\text{cm/s}}{3} \times \left(\frac{500\text{cm}^{-1}}{2\times10^{18}\text{cm}^{-3}}\right) \times \left(2.5 \times 10^{16}\text{cm}^{-3}\right) = \frac{1}{16\text{ps}} \qquad \textit{Eq. 2.2}$$

The calculated stimulated emission lifetime of 16 ps at saturation greatly exceeds the intrinsic spontaneous emission lifetime of a similar semiconductor. At first glance, one might think that to achieve a similar lifetime in an LED one would need to concentrate the zero-point electromagnetic field to the same intensity as that of the saturation intensity of real photons in a laser given above. However, the LED has a major advantage over the laser: in practice a laser operates at less than 10% population inversion, while an enhanced LED can be heavily doped to take full advantage of full upper state population. This is one of the advantages of antenna enhanced spontaneous emission.

The spontaneous emission lifetime of a semiconductor with extreme p-doping and an essentially empty valence band is given by,

$$\frac{1}{\tau_{spon}} = \frac{|qx|^2 n\omega^3}{3\pi\varepsilon_0 \hbar c^3} \approx \frac{1}{700\text{ps}} \qquad \textit{Eq. 2.3}$$

Thus an enhancement factor of approximately 100x is needed for the spontaneous emission rate to exceed the stimulated emission rate, which is readily achievable in many antenna designs (see, for example, Figure 2.21a and b). Missing in this analysis is the quantum efficiency of the device, which can degrade with high doping density as the device becomes Auger limited. However, a large radiative enhancement can compensate for this drop in efficiency. The geometric device parameter *b* (see Figure 2.21a and b) can be adjusted to provide the needed enhancement with no change in antenna efficiency (Figure 2.21c and d). Fine-tuning the parameter *b* will thus allow for an ultra-efficient, high-speed optical antenna-LED.

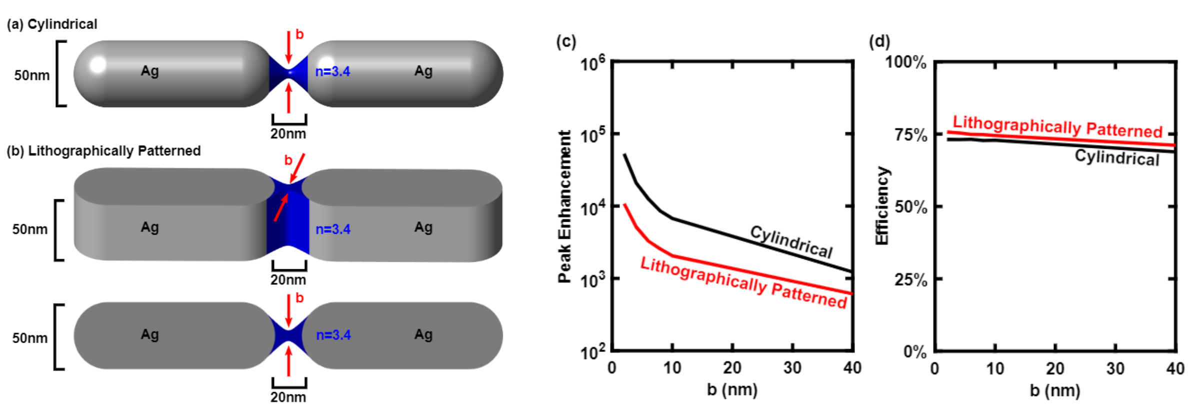

Figure 2.21. Designs for cylindrical **(a)** and lithographically patterned **(b)** optical antennas. The corresponding peak enhancement **(c)** and antenna efficiency **(d)** is given as a function of the geometric device parameter *b*.

IIIb. Coupling of nanoLEDs to Optical Waveguides

The **Wu** and **Yablonovitch** groups at *Berkeley* have continued their close collaboration with the **Kim** group at *MIT* with the goal to realize an optical link by coupling the photoluminescence output of a high-efficiency III-V antenna-LED to waveguides. To address to challenge, the team used electromagnetic design techniques to engineer and optimize coupling efficiencies of nanoLEDs to single mode optical waveguides.

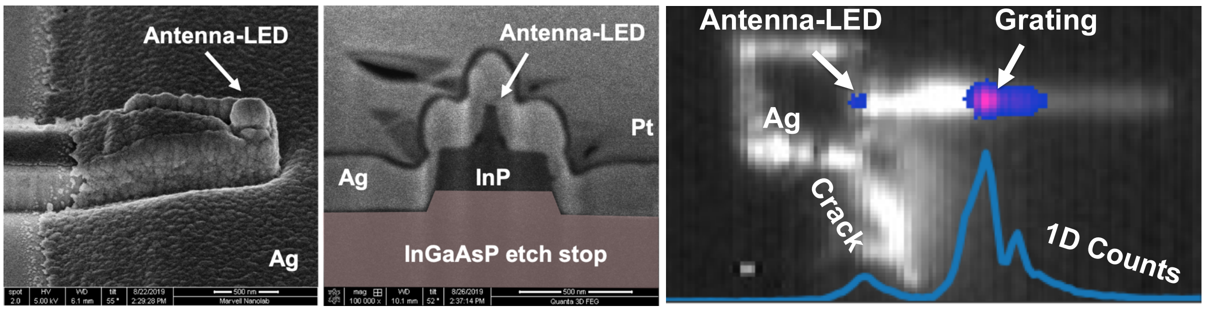

Figure 2.22. Left: Scanning electron micrograph of tapered coupler on InGaAsP etch stop. **Center:** Focused ion beam micrograph showing antenna-LED and waveguide width. **Right:** Dark field image of waveguide coupled antenna-LED. Overlaid, as a heat map, is the light when the device is on – on the left is the not-coupled antenna-LED emission, and on the right is the waveguide coupled light coming from the grating. Finally, the 1D counts are overlaid at the bottom as a solid blue line.

In this period, the nanophotonics group built on these studies and fabricated and tested a waveguide-coupled cavity back slot antenna-LED. The **Kim** group grew all epitaxial materials with different active region designs, as specified by modeling results from the **Wu** and **Yablonovitch** groups. Figure 2.24 (left and center) shows the device before epoxy bonding and substrate and InGaAsP etch stop removal. The dark field outline of the device is given on the right of Figure 2.24, with the overlaid photoluminescence map of the optically pumped device from the 2D InGaAs camera – light was then sent to the cooled 1D InGaAs detector and the photoluminescence counts were overlaid as the solid blue line at the bottom.

Figure 2.23 shows the light from the cooled 1D InGaAs detector again (note that the curve is inverted due to the mirror setup). Using this graph and taking the ratio of the integrated grating counts to the total integrated counts, a waveguide-coupling ratio of 85.9% was calculated, which is an approximation of the waveguide coupling efficiency. It should be emphasized, however, that this calculation is a mathematical construct and not the exact waveguide coupling efficiency. In fact, from initial 3D FDTD simulations, the group believes that this calculation slightly overestimates the true waveguide coupling efficiency. Efforts are currently underway to directly determine the true coupling efficiency.

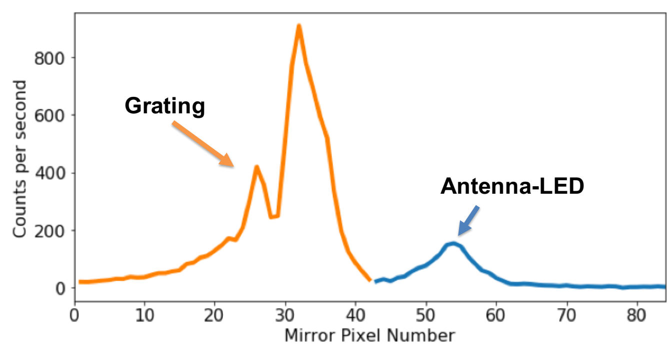

Figure 2.23. Photoluminescence spectrum of waveguide coupled antenna-LED. The solid orange line shows light emission coming from the grating (waveguide coupled light), whereas the solid blue line shows the light not-coupled from the the antenna-LED.

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

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

Guided by theme leader **Jeffrey Bokor** (*Berkeley*), the multi-institutional nanomagnetics team at E^3S addresses these very challenges of magnetics-based switching. In addition to the Bokor group, the research team is comprised of the groups of **Sayeef Salahuddin** (*Berkeley*), **Vladimir Stojanović** (*Berkeley*), **Sakhrat Khizroev** (*FIU*), and **Shan Wang** (*Stanford*). This team takes advantage of spin-transfer torque magnetic tunneling junctions and newly discovered ultra-sensitive current driven switches employing actuated spin-orbit torque (spin-Hall effect) to switch a magnet, which in turn changes a voltage-biased magneto-resistor, producing output current [12]. In addition, the nanomagnetics team employs novel ultra-fast hot-electron switching methods [50-52] to counter the inherently low fundamental switching speed of conventional nanomagnetic devices.

Current magnetic switching devices are limited in speed by the fundamental precessional frequency of ferromagnetic materials, which is generally in the range of 10 GHz, and device-switching speeds are in the range of 1 nanosecond. In contrast, E^3S nanomagnetics researchers from the **Bokor** and **Salahuddin** groups demonstrated that switching of ferrimagnetic compounds could be achieved at picosecond time scales by hot electrons that are excited *via* electrical pulses (Figure 2.29) [13, 51]. This approach can also be extended to ferromagnetic compounds by exchange coupling [53].

In addition, the E^3S nanomagnetics team (**Salahuddin** and **Wang** groups) has been using topological effects as promising avenues to reduce current and identified several topological insulator materials as interesting spin transfer torque candidates. The **Khizroev** group in collaboration with the **Bokor** group has continued research on the fabrication and characterization of square spin-transfer torque based magnetic tunneling junction devices. Nanoparticle-based devices with critical sizes as small as 2 nm were fabricated [22], and have shown superior properties such as tunneling magnetic ratios (TMR) exceeding 1000% ("ON/OFF" ratio equivalent), record small switching current densities (< 1 MA/cm^2), and multilevel devices with improved energy efficiency and information processing capabilities [24].

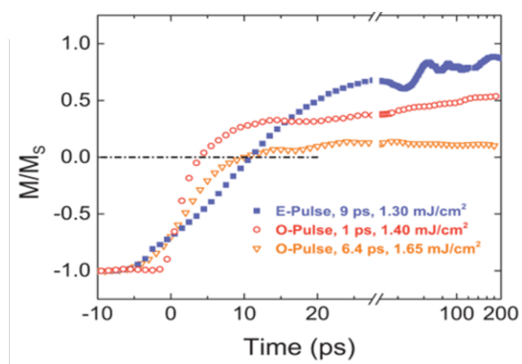

Figure 2.29. Ultrafast magnetic switching behavior of ferrimagnetic GdFeCo as a function of excitation pulse type and width.

The following provides details of period 10 research efforts in the nanoelectronics theme.

IVa. Picosecond Magnetic Switching

In recent years, the **Bokor** group in collaboration with the **Salahuddin** group made several breakthrough discoveries in ultrafast switching of magnetic materials. Building on prior work that has shown that demagnetization in the picosecond time range can be enabled by hot electrons that are excited via direct heating with a short laser pulse [52], the E^3S team developed a more practical approach by injecting hot electrons into the magnet by application of a short, low-voltage electrical pulse (Figure 2.29). This approach enabled electrical ultrafast switching of ferrimagnets [13, 50, 51], ferromagnetic alloys including GdCo and GdTbCo, and ferromagnetic Pt/Co multilayers by exchange coupling to GdFeCo [53].

The ultimate goal of the E^3S nanomagnetics team is to inject hot electrons into the magnet by application of a short, low-voltage, on-chip electrical pulse. Conventional CMOS scaling is projected to reach transistor speeds in the range of a few picoseconds, so such electrical pulses will be available on-chip. A joint collaboration was formed among the **Bokor**, **Salahuddin**, and **Stojanović** groups to integrate magnetic device structures on advanced CMOS chips in order to test magnetic switching and readout triggered by electrical pulses generated directly by CMOS circuits. Two challenges have to be overcome toward this goal: (1) Integration of an electrical readout into the circuit structure, and (2) reduction of both the switching energy and current to be compatible with CMOS technology. In fact, calculations revealed that energies and currents for the electrical switching of magnets could be as low as ~3.5 fJ and ~10's of μA, respectively, for a $(20\ nm)^3$ cell size.

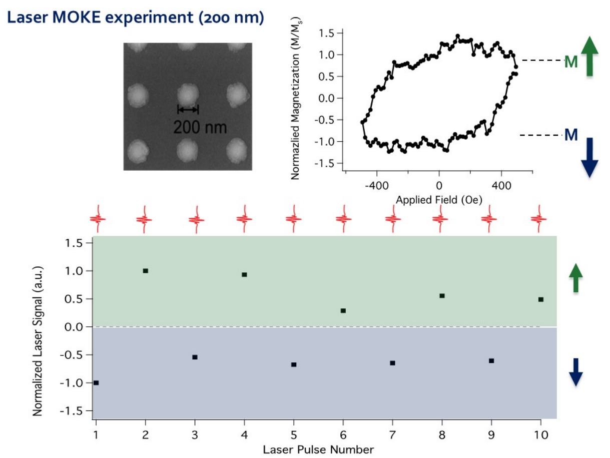

Figure 2.30. Top left: SEM image a 200 nm GdCo nanodot array. **Top right:** Out-of-plane magnetic hysteresis loop of GdCo 200 nm dots measured by laser MOKE. **Bottom:** Single shot switching experiments of 200 nm dots by laser MOKE, indicating toggle switching between up and down magnetization states with each subsequent pulse.

In period 10, the **Bokor** and **Salahuddin** groups have made further significant progress to solve the abovementioned challenges. A main focus was to investigate scaling of electrical switching of GdFeCo into nanometer range in order to reduce the required switching current. This required integrating an electrical readout into the circuit structure. The team succeeded in fabricating nanodots of GdCo down to 50 nm in diameter while maintaining good magnetic properties including perpendicular anisotropy as the size of the dots is reduced. For these GdCo alloys, ultrafast all-optical switching behavior was observed in nanoscale dots fabricated in arrays as small as 200 nm in diameter (Figure 2.30). This was the detection limit for reliably detecting the magnetic state of the dots [54].

In order to test electrical switching of individual dots, suitable microwave circuits for delivering the required short electrical pulses to the device need to be designed. Furthermore, detecting the magnetic state of individual dots needs to be achieved. The **Bokor** group has continued to make progress in this effort, and successfully fabricated and tested a Hall-cross device geometry capable of measuring the magnetization in GdCo nanodots down to 50 nm diameter. Simulation studies of pulse propagation on microwave striplines have guided the design for the integration of this Hall bar structure into a microwave stripline that will generate the picosecond electrical pulse and deliver it to the Hall bar. Fabrication of these structures has turned out to be rather challenging and is currently still in progress.

IVb. Spin-Orbit Torque Switching

The main focus of the **Salahuddin** group is to devise ways to reduce current needed to switch magnets using a spin-orbit torque (SOT). In period 10, the group explored a new concept of exploiting synthetic anti-ferromagnets to induce switching in spin-orbit-torque devices without needing an external magnetic field. Based on micromagnetic simulations, they showed that it is possible to achieve spin–orbit torque field-free switching of a synthetic antiferromagnet comprised of two ferromagnetic (FM) layers with perpendicular magnetic anisotropy, sitting on top of a conventional antiferromagnet [20]. Field-free magnetization reversal is propelled by the competing exchange fields and spin torques. Although some antiferromagnetic coupling is necessary to switch both ferromagnetic layers, strong Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions inhibits the switching process due to the strong repelling forces experienced by both FM layers. The switching happens through domain nucleation and propagation and is aided by Dzyaloshinskii–Moriya interactions. The overall heterostructure is applicable in conjunction with a magnetic tunnel junction, where the free layer is comprised of the proposed synthetic antiferromagnet. Figure 2.31 shows the switching dynamics of the two ferromagnets within the synthetic antiferromagnet as a current is supplied laterally. For a large phase space of applied current and exchange coupling strength between the two magnetic layers of the antiferromagnet a complete switching is possible.

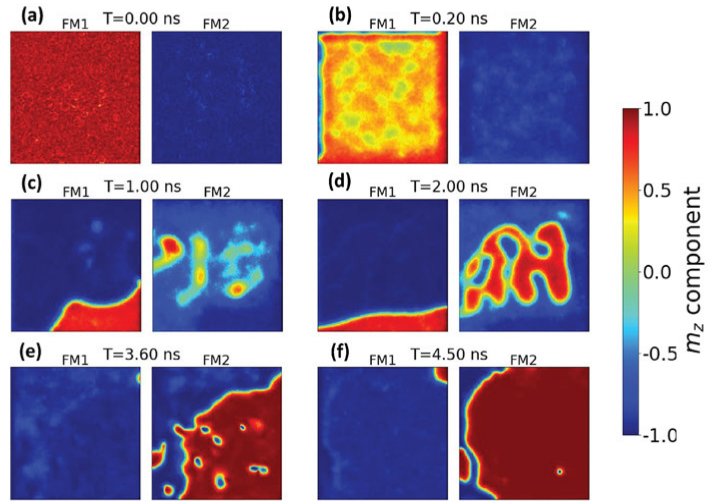

Figure 2.31. Distribution of m_z components in FM1 and FM2 (of the synthetic antiferromagnet) with J_x = 4.4 × 10^8 A/m^2 and J_{RKKY} = −0.014 J/m^2. The color scale represents the final state of FM2: red is "up", while blue is "down".

The group of **Shan Wang** (*Stanford*) focuses on experimental research for demonstrating SOT switching of adjacent ferromagnets, especially magnetic-tunnel-junction (MTJ)-compatible CoFeB and NiFe materials, in the SmB_6 and heavy metal systems. Of particular interest are topological materials, which have recently emerged as an effective spin current generator for SOT-MRAM applications with sub-ns and fJ-level write performance. However, the topological insulators that have been investigated intensively in the past decade face great challenges when integrated into the MRAM cell. The high resistivity of Bi_2Se_3/$Bi_xSe_{(1-x)}$ grown by molecular beam epitaxy and sputtering (more than 4,000 $\mu\Omega$cm at 5 nm thickness at room temperature) [55-57] introduces large parasitic resistance when used as a write line in SOT-MTJ arrays. In addition, there are no topological materials known to date that can sustain their large charge-to-spin conversion efficiency (ξ_ST) values after thermal annealing, which is an integral part of the CMOS back-end-of-line process. In this period, the **Wang** group achieved room temperature high charge-to-spin conversion efficiency in sputtered WTe_x-based heterostructures that can withstand 300 °C annealing process. They successfully demonstrated damping-like SOT-induced magnetization switching using ion-beam sputtered WTe_x thin films and found that using a WTe_x/Mo/CoFeB/MgO-based heterostructure, the in-plane magnetization direction of the CoFeB layer can be detected electrically using the unidirectional spin Hall magnetoresistance (USMR) effect (Figure 2.32). The field dependence of USMR (Figure 2.32 top) shows that the USMR effect originates from the scattering between SOT spin currents from WTe_x and magnons in the CoFeB layer. Room temperature switching with a current density of 1 MA/cm^2 has been

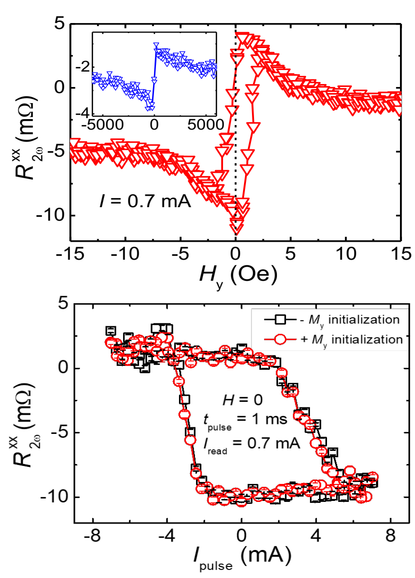

Figure 2.32. USMR field dependence (**top**) and USMR detection of the magnetization switching (**bottom**) in WTe_x/Mo/CoFeB/MgO heterostructures.

demonstrated (Figure 2.32 bottom). The charge-to-spin conversion efficiency was found to be around 0.5 using the critical current density values.

IVc. Magnetic Tunneling Junction Devices

The **Khizroev** group, in collaboration with the **Bokor** group, has continued research on spin-transfer torque (STT) MTJ devices made of ferrimagnetic $CoFe_2O_4$ nanoparticles sandwiched between magnetic layers of traditional high-anisotropy CoFeB compositions [21]. Measured I-V behavior confirmed the single-electron behavior of such junctions. In the past period, the team built first batches of nanoparticle-based STT-MTJ devices with critical sizes as small as 2 nm, which were driven by quantum physics. They exhibited superior properties such as extremely high equivalent "ON/OFF" ratios with tunneling MR values exceeding 1000%, and record low switching current densities (< 1 MA/cm^2) [22]. Furthermore, this nanoparticle STT-MTJ concept combined with electron-beam lithography nanofabrication was used to write information not into two but into three layers (Figure 2.33) and the written/read back information had a ternary (not binary) signal format. To date, the information has been read back optionally using the giant magnetoresistance (GMR) and/or tunneling magnetic resistance (TMR) effect, the MOKE effect, or MFM-based reading from the top surface [22-24].

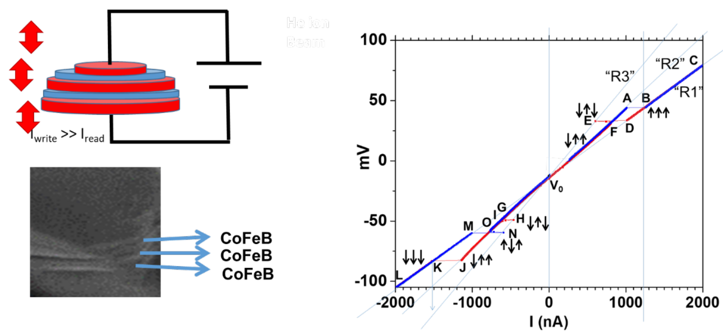

Figure 2.33. Left top: Equivalent circuit showing a three-layer STT-MTJ device for ternary signal processing. **Left bottom:** TEM image of a nanoparticle-based STT-MTJ device with two magnetic interfaces. **Right:** *I-V* curve showing ternary signals from the three-layer STT-MTJ. The information was read back through the TMR effect.

In this period, the team performed detailed studies of the three read back options. Because of the different physics, these three effects provide different numbers of signal levels. For example, the currently used approaches of TMR and MOKE provide three and eight signal levels, respectively, while with MFM, four signal levels could be read. The TMR effect, due to the tunneling resistance dependence on the relative orientations of the magnetizations at each interface in the 3-layer junction, is substantially simpler to implement compared to the MOKE effect. For comparison, the MOKE reading mechanism requires a highly polarized optical source with all the accompanying complicated electronics to extract the signal from the multilayer stack. Therefore, the goal will be to improve the reading via GMR and/or TMR and increase the number of signal levels to more than three.

This collaborative, inter-institutional work demonstrated the feasibility of using the STT effect to write multilevel information into a multilayer MTJ stack via a spin-polarized current and read back the multilevel information. These results will pave the way for a new computing paradigm, which uses spin polarized currents to write and read back multilevel signal information. Unlike the traditional binary signal information processing, multilevel signal processing, with more than two signal levels, is believed to be more energy efficient as well as much better suitable for realizing novel computing paradigms such as neuromorphic computing – brain inspired computing.

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

Va. System Implementation of E^{3}S Devices—Applications in Edge Computing

In this period, the collaborative research efforts of the **Stojanović**, **Liu**, and **Bokor** groups has continued on system integration of E^{3}S nanomechanical and nanomagnetic devices, which possess the opportunity for inherent non-volatility. In particular, the team has focused on the integrated circuit implementations of the systems in the so-called "edge compute" scenarios, where the sensory and computation functions are severely energy limited. 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. For example, the **Stojanović** and the **Liu** groups have investigated the use of NEM-based relays for applications as look-up tables (LUTs) and embedded memories. Current research also includes arrays of reconfigurable NEM-based interconnects for machine learning applications.

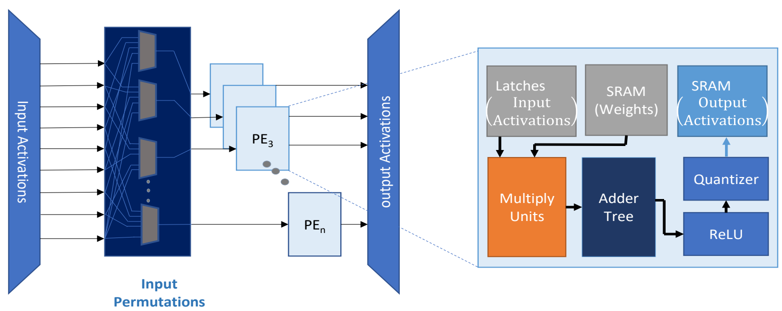

Figure 2.34. Generator micro-architecture illustrating the routing matrix and processing elements.

In the last period, the **Stojanović** group has focused on hardware macros that support efficient implementations of fully connected and convolutional layers with enough re-configurability to allow mapping of various popular networks. At the same time they have introduced algorithmic modifications (such as permutation-based transforms, pruning and smart quantization) to allow mapping of these highly irregular computations onto regular in-memory structures implemented with non-volatile memory relays and spin devices. Setting-up these efficient microarchitectures enables to evaluate various device flavors in a very structured and well-confined architecture context that focuses on efficiency of local storage and computation without large control overheads that usually obfuscate the gains obtained from the raw device performance. The accelerator generator framework (Figure 2.34), which the **Stojanović** group put in place during the previous period, now serves as the baseline for the generation of new designs utilizing the nanomagnetic and nanomechanical devices, as well the tool for benchmarking of their performance vs. CMOS-only designs. A per-layer comparison for a state-of-the-art neural net ResNet-50 revealed 10-150x speed-ups of the structured sparsity architecture developed by the **Stojanović** group compared to unstructured sparsity state-of-the-art architectures, depending on the layer of the neural net. Similar results are found for VGG-19. Figure 2.35 illustrates the evaluation of the energy-efficiency of the above architecture when implemented with NEM relays, used for arithmetic and memory functions. The same figure shows the implementation of the NEM relays chip in 16 nm CMOS process [58]. Being able to quantify the application-level benefits of these emerging device technologies will hopefully both help stimulate the interest in their adoption (and further process developments required to support it), as well as provide further important guidance to E^{3}S researchers on the critical device design parameters that need to be further optimized for a given application and architecture.

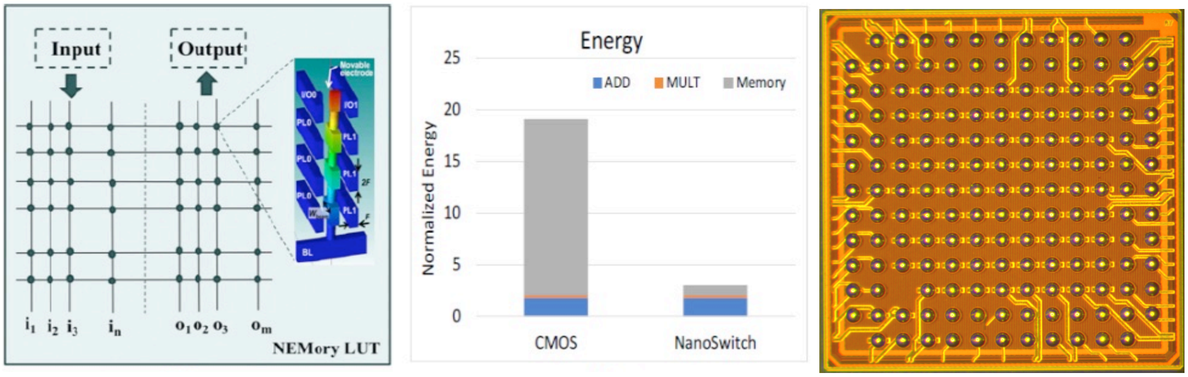

Figure 2.35. Energy projections of NEM switch-based implementation (**left**) of the structured-sparsity accelerator architecture compared to a CMOS implementation (**center**). **Right:** A 2.5mm x 2.5mm NEM relay chip implemented in 16 nm CMOS process.

Vb. Analog Machines for Digital Optimization

In period 10, the **Yablonovitch** group started a research project on developing continuous-time analog machines for digital optimization. Such analog machines have attracted significant interest for solving the computationally hard Ising Hamiltonian optimization problem, which describes the total interaction energy of any given network of coupled magnetic spins (Figure 2.36). The Ising optimization problem asks one to find that configuration of spins that achieves the global minimum of the Ising Hamiltonian merit function compared to all other configurations. The complicating factor that makes the problem hard is the constraint that the spins are restricted to take only the discrete values +1 or -1.

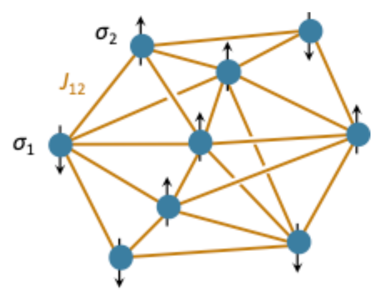

Figure 2.36. Model of an Ising spin network.

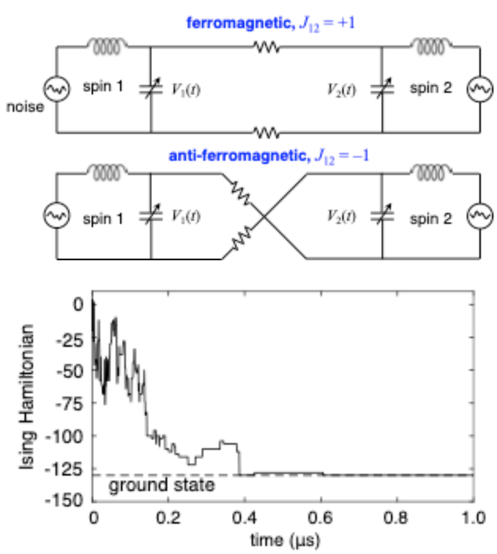

Figure 2.37. Top: Schematic of the LC oscillator system for a 2-spin problem. **Bottom:** Example of a 32-spin problem solved by the Yablonovitch system.

The motivation for designing analog machines for the Ising problem is that there are physical principles in the domains of optics and electrical circuits and many other systems that be exploited to achieve orders-of-magnitude time speedups over digital algorithms while matching the quality of solutions obtained by them. The **Yablonovitch** group designed and analyzed an electrical LC oscillator-based Ising machine (Figure 2.37, top) [59]. Key findings in this period were that all systems previously developed [60-64] were in fact physical implementations of the well-known method of Lagrange multipliers in optimization theory. Furthermore, optimization of a much larger class of merit functions beyond the Ising Hamiltonian can be performed by appropriate modifications of the above systems (Figure 2.37 bottom). This reinterpretation led the team to the conclusion that they possess now fast analog ways of performing Lagrange multiplier optimization, which would find immediate application in several areas that involve optimization such as control systems, operations research and artificial intelligence.

2b. Table 2.3. Performance Against Metrics

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
Research	Multi-PI projects	P2: 30% P5: 75% P6: 50% P7: 60% P8-P10: 70%	44%	67% (14)	55% (12)	64% (14)	76% (13)	65% (11)	79% (15)	89% (16)	88% (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)	72% (13)	53% (9)
	Publications with authors from multiple institutions	P3: 12 P4: 3 P5-10: 5	0	0	1	1	4	4	3	3	5
	New joint research funding awards	P6: 1 P7: 0 P8-P10: 1	(new for P6-10)				0	3	1	1	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.*

In Period 10, E^3S has continued to be a highly collaborative environment, exemplified by the high number of both multi-PI and multi-institutional projects—both exceeding again the target numbers set in the Center's Strategic Plan. In addition, the upward trend in co-authorship in journal publications and conference proceedings, in particular between authors from different E^3S institutions, has continued in this period. So far, the Center published 32 articles (including six submitted) in this reporting period, 39 percent of these articles have two or more faculty co-authors, and five of these articles are inter-institutional publications. In this period the Center will reach the target number of joint multi-institutional journal publications. As discussed earlier, this positive trend is a direct result of the collaboration-fostering steps introduced by the Center leadership in recent years: The formation of E^3S Inter-Institutional Postdoc program, and an increase in available E^3S Rotation Program positions for students and postdocs to spend mid-term (8-12 weeks) research stays at an E^3S partner institution other than their home institution.

2c. Forthcoming Research in Period 11

Entering the final six months of the Center for E^3S, no changes in key personnel (i.e. senior investigators/faculty) and no changes in the current main research directions of the four themes and system integration are planned. Research efforts will be focused on completing current projects according to the Center's strategic research plan and the longer-term Center legacy efforts.

Center for Energy Efficient Electronics Science

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

In period 11, 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** (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 continue to investigate the VNW geometry to achieve III-V transistors with steep subthreshold characteristics for both MOSFET and TFET structures. In particular, the group will focus on in-situ atomic-layer etching and atomic-layer deposition of the gate dielectric for advanced 3D transistors. Expected major milestones are (1) the development of atomic-layer etching of antimonide semiconductors, (2) the fabrication and characterization of InAs/GaSb staggered-bandgap vertical nanowire Esaki diodes and tunnel FETs, and (3) the formation of new mushroom top contacts for InAs/GaSb vertical nanowire devices.

- *Chalcogenide TFETs:* In the current period, the **Kong** group has investigated the direct patterning of the monolayer MoS_2 growth during the synthesis step. This method shows the potential of using the pre-patterned substrates as a master template for the repeated growth of monolayer MoS_2 patterns. The goal for period 11 will focus on extending this patterning method to other 2D materials to provide a facile method for the repeatable direct synthesis of 2D materials for future electronics and optoelectronics. Traditional semiconductor fabrication methods, such as lithography and etching, have been sufficient for the needs of integrated circuits over past decades. Their applicability has also been demonstrated in emerging 2D materials, which offers facile processing over large lateral dimensions, while unique and remarkable properties due to the confinement within atomic thicknesses. Nevertheless, each fabrication step adds cost to the manufacturing and increases the possibility of quality degradation. The direct patterning method of the **Kong** group not only saves the step for lithography and patterning, it also allows the repeated use of the template mask which leads to cost-effective fabrication in the future.

  The successful demonstration by the **Javey** group of near unity photoluminescence quantum yield of as-exfoliated MoS_2 and WS_2 monolayers by electrostatic doping, without any chemical treatment, demonstrated that, even in the presence of defects in sulfur-based TMDCs, neutral exciton recombination could be entirely radiative [16]. However, when the monolayer is full of trions, the quantum yield is $< 0.1\%$, indicating a high trion non-radiative recombination rate. Therefore, excitons and trions should have different diffusion properties and interactions with disorder. The **Javey** group will team up with the **Bulović** group at *MIT* to measure the spatial, temporal and spectral character of the photoluminescence emission under different gate voltages and illumination conditions. With these data in hand, the team expects to gain a comprehensive understanding of the diffusion of different quasi-particles in these monolayers. In addition, the **Javey** group will explore new materials for energy filtering in TFETs. A large band-gap insulator with a defined defect level placed between the source and channel can act as an energy filter and selectively inject carriers with specific energy. With correct band alignment, both the on current and subthreshold swing will be improved. One such choice for 2D van-der-Waals tunnel FETs could be few-layer hBN with mono-nitrogen vacancy, where the mid-bandgap level created near the Fermi level conducts current. MoO_x also has a large bandgap with a defect level inside the forbidden gap. This project will enable to explore and categorize different wide bandgap materials on the basis of their performance in energy filtering in TFET.

- *Graphene Nanoribbon TFETs:* The **Fischer** group (guided by theoretical input of the **Louie** and **Yablonovitch** groups, and device fabrication by the Bokor group) will continue to explore and expand the rational bottom-up synthesis strategy for graphene nanoribbon (GNR) tunnel junction devices. The group recently demonstrated the ability to covalently fuse GNR segments exhibiting different topological phases into atomically defined heterostructures that feature symmetry-protected localized interface state and metallic or semi-metallic character. The **Fischer** group will design and synthesize the next generation of metallic GNRs based on a mirror symmetric monomer precursor. This will have the advantage that the relative orientation of the monomer in the growing polymer chain reliably yields metallic GNRs rather than semiconducting GNRs resulting from monomer misalignment during the polymerization. In collaboration with the **Bokor** group, wet and dry transfer processes of GNRs onto insulating substrates will be continued to enable measurement of the conductance of metallic GNRs in a device setting.

The **Louie** group will further study GNRs with metallic narrow band by first-principles calculations, and investigate the Coulomb repulsion of electrons on the relatively localized orbitals forming the narrow band metallic GNRs. The goal is to prevent the designed structures from developing band gaps, i.e., forming Mott insulators. In general substrate screening will reduce the Coulomb charging energy without affecting the hopping term. In addition, the group will design a GNR based structure of a quantum dot coupled with GNR leads with metallic narrow band. They will calculate the broadening of the lineshape of an energy level in the quantum dot and test possible faster-decaying non-Lorentzian lineshapes.

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

The nanomagnetics team consisting of the research groups of **Tsu-Jae King Liu**, **Junqiao Wu**, **Vladimir Stojanović** (all *Berkeley*), **Vladimir Bulović**, **Jeffrey Lang**, **Farnaz Niroui**, **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").

- *Low-Voltage Relay Design and Integrated Circuit Operation:* Based on recent breakthroughs in ultra-low-voltage operation of NEM-based switches, the **Liu** group, in collaboration with the **Stojanović** group will systematically study the impact of ultra-low-voltage operation (V_{GS} and V_{DS}) on the stability of relay on-state resistance at room temperature. Since contact (impact) velocity is lower for ultra-low-voltage operation, alternative contacting materials, which are softer, will be investigated to ascertain whether they provide for more stable on-state resistance with adequate switching endurance. Following the discovery of greatly improved NEM relay characteristics at cryogenic temperatures, the team will also explore operation of relays and integrated circuits at temperatures below 1 Kelvin. The goal is to evaluate their compatibility with milli-Kelvin temperatures required for quantum computing.

  The **Wu** group will continue research on exploring NEM relay coatings to minimize contact stiction and thus hysteresis voltage. In period 11, the group will focus on 2D chalcogenide materials as coatings. In particular, they plan to thoroughly study the deep electron traps in MoS_2-WS_2 layers, including quantify the energy level, the capture cross section, the density, the meta-stability, and the atomic configuration of the related defects. They will work together with DFT experts, device experts and TEM experts to establish a full picture of these point defects in MoS_2-WS_2 and their alloys.

- *Squitch Project:* The **Squitch** team (the **Bulović**, **Lang**, **Niroui**, and **Swager** groups at *MIT*), in collaboration with the **Liu** group at *Berkeley*, will focus on the development, characterization and use of all-graphene squitches during the final period of the Center. This will include both two- and four-terminal squitches. The research will focus on four general activities: The first activity is squitch fabrication, specifically four-terminal squitch fabrication, and the improvement of yield if possible. At present, however, fabrication yield appears to be adequate to support other research activities. The second activity is to investigate the impact, if any, of electromigration on squitch performance. The use of all-graphene squitches, which cannot exhibit electromigration, is critical to this investigation. The third activity is to demonstrate simple circuits based on squitches, the first of which should be a ring oscillator with which to measure the switching speed of squitches. The final activity is molecular engineering, namely the search for a molecular layer the yields the greatest current modulation without exhibiting hysteresis (for low-voltage operation) or switching degradation (for long life).

- *Stritch Project*: The inter-institutional **Stritch** team with project leader **David Zubia** (*UTEP*) and the *Berkeley* research groups of **Liu**, **Javey**, and **Wu** will continue to develop MEMS switches based on stretching 2D materials, in particular, transition metal dichalcogenides (TMDCs). With the new actuator designed completed in the current period and device fabrication underway, the main goal of period 11 will be to complete the new stritch device fabrication and achieve >>3000X increase in conductivity upon stretching of the incorporated MoS_2 TMDC layer. Furthermore, the team will conduct detailed electrical and optical characterization studies of strained the MoS_2 layers, and expand the stritch concept to other TMDCs such as TaS_2. In general, the UTEP team will use the MEMS actuator as a platform for future collaborative research in a wide range of MEMS and TMDC research areas.

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

The nanophotonics team consisting of the research groups of **Ming Wu**, **Eli Yablonovitch** (both *Berkeley*) and **Jeehwan Kim** (*MIT*) will continue research toward on-chip few-photon optical communication between electronic switches at unprecedented efficiency levels of a few hundreds of photons per bit using to concept of antenna-enhanced nanoLEDs from novel III-V heterostructures, optimized waveguide coupling, and integration of nanoLEDs on silicon.

- *Digital-to-Digital Optical Link:* In previous period, the **Wu**, **Stojanović**, and **Yablonovitch** groups teamed up to simulate a full digital-to-digital optical link with inclusion of the receiver. Reasonable values were assumed for the photodiode [65], and the CMOS receiver's extrinsic current-unity gain. The receiver model considered not only resistor thermal noise and transistor FET noise, but also the input swing sensitivity required to have an output rail-to-rail signal. All of these metrics combined to yield a topology and data-rate specific energy-per-bit (E/b) both for the receiver side and transmitter side. For each data-rate, an optimization was performed to find the minimum E/b sweeping over the number of linear amplifiers, the number of interleaves, and the FET sizing. Based on these outcomes, the nanophotonics group led by the **Wu** group, and in collaboration with the **Yablonovitch**, **Stojanović**, and **Kim**, will work on experimental demonstration of a full optical link. An important requirement will be to have an electrical input and output. At first, the group will concentrate on fabricating an electrically injected waveguide-coupled device. This will be followed by closing the link with a large-area photodiode with the same device structure as the nanoLED. Finally, in order to demonstrate a more efficient full link, the team will create a low capacitance photodiode, which may benefit from integrating the device with another material. This can be done by coupling light from the indium phosphide waveguide to a silicon waveguide in order to route to the low capacitance photodiode.

- *Integrating nanoLEDs on Silicon:* The **Kim** group at *MIT* will work closely with the **Wu** and **Yablonovitch** groups at *Berkeley* on integration of antenna enhanced nanoLEDs to Si CMOS. The complexity of integration with nanoLED, waveguide and Si requires a novel innovation in semiconductor heterointegration. In recent years, the **Kim** group has developed a universal technique to transfer epitaxial films of compound semiconductors to be interfaced with Si CMOS. This new technology, referred as 'two dimensional layer transfer', relies on the use of graphene as a platform for semiconductor epitaxy. Based on this technique, epitaxial stack for the nanoLED device will first be grown on a graphene coated InP substrate, then transferred to a Si CMOS with a low-index material to help bond and define the waveguide for the nanoLED. Once the Si CMOS, cladding material and III-V stack has been integrated together, the III-V stack can undergo CMOS-friendly processes to fabricate the nanoLED. In period 11, the group aims to demonstrate (1) InP buffer layer grown on top of graphene suitable for growing the nanoLED epitaxial stacks, and (2) the feasibility of exfoliating and bonding the epitaxial buffer film on top of a Si substrate. The longer-term goal is to fabricate the antenna-enhance nanoLED on top of the transferred III-V epitaxial film with demonstration of wave-guide coupling.

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

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

- *Picosecond Magnetic Switching and Integration with CMOS:* The **Bokor** group, in collaboration with the **Salahuddin** and **Stojanović** groups, will built on the significant progress in the current period on miniaturization of the magnetic GdCo and GdTbCo dots used for ultrafast switching. In the current period, the **Bokor** group has successfully fabricated and tested a Hall-cross device geometry capable of measuring the magnetization in GdCo nanodots down to 50 nm diameter. In period 11, the Hall-cross device fabrication will be optimized with the goal to reliably obtain electrical switching results on GdCo nanodots with <50 nm diameter, and thereby determine the scaling behavior of the electrical switching current with dot size. The group will also study ultrafast spin-Hall effect. The plan is to use picosecond electrical pulses to switch ferromagnets directly using a combination of ultrafast heating and demagnetization of the ferromagnet with deterministic switching of the magnetization as it recovers due to the spin injection by spin-Hall effect.

- *Spin-Orbit Torque Switching:* The **Salahuddin** and the **Wang** groups will continue to investigate topological effects for energy efficient computing and spin orbit torque (SOT) switching and energy efficient computing. Regarding the latter, the **Salahuddin** group will start to leverage E^3S work in the last few years on the charge current control of small magnets for energy efficient learning machines (see also *2cv. System Integration*). The **Wang** group plans to study comprehensively the origin of the large SOT found in sputtered WTe_x by varying the thickness of WTe_x, and by low temperature magnetoresistance, and temperature dependent resistance measurements. The size dependent switching behavior (down to 10 nm), ultrafast switching (< 1 ns), multilevel switching, and possible field-free switching will be investigated. Furthermore, the group plans to fabricate an asymmetric synthetic ferrimagnet or exchange coupled nanostructure that will enable field-free spin-orbit torque magnetization switching of the free layer in a perpendicular magnetic tunnel junction. Both extensive simulation and experiment will be carried out during period 11. Finally, they will explore combining SOT and VCMA in in-plane MTJ for logic in memory and energy efficient AI hardware applications.

- *Magnetic Tunneling Junction Devices:* Based on the successful demonstration of spin torque transfer (STT) MTJ devices with incorporated ~2 nm $CoFe_2O_4$ nanoparticles, in period 10, the **Khizroev** group plans to build a complete STT-MTJ device capable of multilevel signals in which spin polarized currents are used both for writing and reading. For this, STT-MTJ devices will be built from non-traditional materials, which will be better suited for the proposed 3D configuration. Particular focus will be on (1) extending the three-level 3D nanostructure devices to four and more layers, and (2) using STT to write and GMR/TMR to read back the multilevel signal.

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

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

- *System Implementation of E^3S Devices:* In period 11, the **Stojanović** group will continue research into system integration of E^3S nanomechanical and nanomagnetic devices. The goal is to explore the opportunity for inherent non-volatility, which may fundamentally alter the balance between computing, communication, and storage for a given application. The goal is to provide both a path to quantifying the benefits of the emerging device technologies at the circuit/system level as well as guidance to the device designers on which device design parameters are critical to improve from the system level perspective. In particular, the group will focus on comparative analysis of the NEMory, ReRAM, and CMOS-based memories for the large multi-headed attention neural net for natural language processing applications, which is ideal for edge-based inference devices.

- *Analog Machines for Digital Optimization:* The **Yablonovitch** group will further explore the use continuous-time analog machines, such as the electrical LC oscillator-based Ising machine developed in the current period, for digital optimization. After demonstrating successful application of their Ising machine by solving a 32-spin problem, the focus in the next period will be on optimization of a much larger class of merit functions beyond the Ising Hamiltonian. The group will use analog ways of performing Lagrange multiplier optimization for applications in control systems, operations research and artificial intelligence.

- *Stochastic Boltzmann Machines:* In period 11, the research plans of the **Salahuddin** group will include stochastic Boltzmann machines—an implementation of the Ising model with stochastic units. This work will be based on the demonstration that a conventional transistor coupled with a properly designed spin orbit torque (SOT) magnetic tunnel junction (MTJ) device could be used to implement the stochastic units (neurons) needed for the Boltzmann machine [25]. Here the SOT is used to bias the stochastic switching of the magnet, allowing for the 'weighting' of the resistance seen through the MTJ. The group will work on SOT devices to reduce the current needed to deflect magnetization, which will reduce the power consumption while being used as a stochastic neuron. In addition, the potential of using antiferromagnets in the SOT device will be examined. The main motivation is to increase the speed of stochastic flip-flopping of the magnetic order, which, for an antiferromagnet, can be two orders of magnitude higher than for a typical ferromagnet. This will reduce the 'correlation time', i.e., the time needed for the Boltzmann machine to complete one cycle of computation.

III. EDUCATION

1a. *Goals and Objectives*

The primary element of the Education goal is the training of Ph.D. and M.S. 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. Additionally, the Center aims to prepare high school and undergraduate students to pursue research and further research in the energy efficient electronics field. This will increase the pipeline of diverse students pursuing technical disciplines and contribute 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 2019 E^3S Annual Retreat included a presentation on our current education programs, as well as a breakout session and discussion regarding the Center's educational legacy. 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. Led by the Center's new Associate Director for Education**, Nicole McIntyre** *(Berkeley)*, retreat attendees reaffirmed the Education strategy that builds on the development of a pipeline of undergraduates who will be interested in research and graduate education. Each theme group then collaborated on developing the Center's online legacy materials.

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 Periods 3-5: 50% Period 6: 15% Period 7: 30% Period 8: 40% Period 9: 50% Period 10: 15%
	Students and postdocs participating in education and diversity programs *(discontinued in the 2nd five years)*		
	Students accessing online courses of the Center *(new)*	Yearly beginning in Period 6	Period 6: 0 Period 7: 15 Period 8: 0 Period 9: 15 Period 10: 0
	Undergraduates who pursue advanced degree in science and engineering	Yearly beginning in Period 3	Period 3: 5% Period 4: 30% Period 5: 35% Period 6: 40% Period 7: 45% Periods 8-10: 50%

	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Yearly beginning in Period 3	Period 2: Baseline Period 3: 5% Periods 4-5: 80% Periods 6-10: 85%
	Pre-college students who pursue a bachelor's degree in science and engineering	Yearly beginning in Period 3	Period 3: Baseline Periods 4-5: 70% Periods 6-9: 80% Discontinued in Period 10
	Students and postdocs serving in leadership roles in the Center	Yearly beginning in Period 2	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Periods 6-8: 30% Period 9: 20% Period 10: 15%

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

1c. *Problems Encountered*

Prior Associate Director of Education, **Lea Marlor** (*Berkeley*), left the Center in April 2019 to pursue a doctorate degree in Engineering Education Research. **Nicole McIntyre** joined E^3S and filled this role seven week later, at the beginning of the summer research programs. As such, her efforts were initially focused on learning about and administering the summer programs.

2. *Educational Activities*

The Center for E^3S graduated six graduate students and six postdoctoral researchers in period 10. Additionally, ten former participants of the Center's E^3S REU or ETERN program completed their Bachelors' degrees. To date, E^3S has graduated 210 participants (82 undergraduates, 75 graduate students, and 53 postdocs) and supported 97 students through the community college transfer process. These students and postdocs have gone on to pursue careers in industry, academia, and national research laboratories (see Graduates Table, Centerwide Output). During their time in the Center, these alumni have benefited from the formal and informal training programs and opportunities, including mentoring opportunities, science communication training, and the Professional Development Program.

The Center also offers a variety of informal training opportunities for graduate students and postdocs including: presenting at seminars and during Center events; mentoring of undergraduates; travel to technical conferences; group analysis of competing research; participating in the REU intern selection process; creation of video lectures for high school students; and co-authoring the Center's eBook. In period 10, 30 graduate students and postdocs took advantage of these practical training opportunities. 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 10, 20 students and postdocs received training in these areas. These participants included both Center members and affiliates.

Given the number of training 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. By completing training and/or professional development in different areas, a student or postdoc can document the skills they learned during their time in the Center with a Leadership Certificate.

Center Director **Eli Yablonovitch** *(UC Berkeley)* continued to teach his Spring graduate course at UC Berkeley in period 10. This courses on low energy electronics focuses on E³S topics and perspectives. In addition to three of the Center's graduate students, 12 other UC Berkeley graduate students enrolled in the course and learned about the Center's research topics.

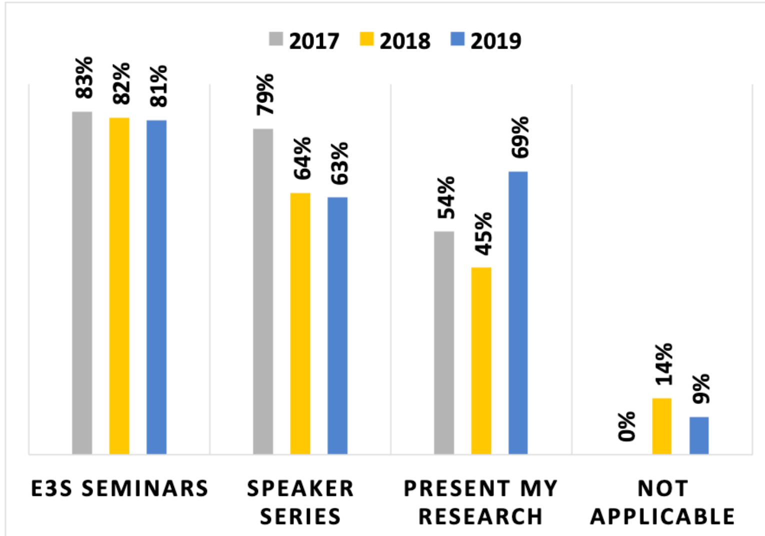

Figure 3.1. Graduate students and postdocs indicated the Center's educational activities are sharpening their understanding of low energy consumption device science and technology.

The E³S 2019 survey of graduate students and postdocs reaffirmed previous findings: the Center enhances members' understanding of low energy consumption device science and technology (Figure 3.1). Membership in the Center also facilitates participants' ability to collaborate with colleagues from different departments and institutions; for 41% of respondents this collaboration has led to, or will soon lead to, a joint publication. Additionally, joining the Center has positively affected graduate students and postdocs' non-technical abilities, such as working in diverse teams, project management skills, and communication skills (Figure 3.2).

Undergraduate members and affiliates of the Center are able to access research opportunities through the E³S Internship (ETERN) and the International E³S Internship (iETERN) programs. These programs are intended to inspire students' continued interest in undergraduate research and graduate studies in the energy efficient electronics field. During period 10, two students participated in the paid 10-week ETERN program during the academic term.

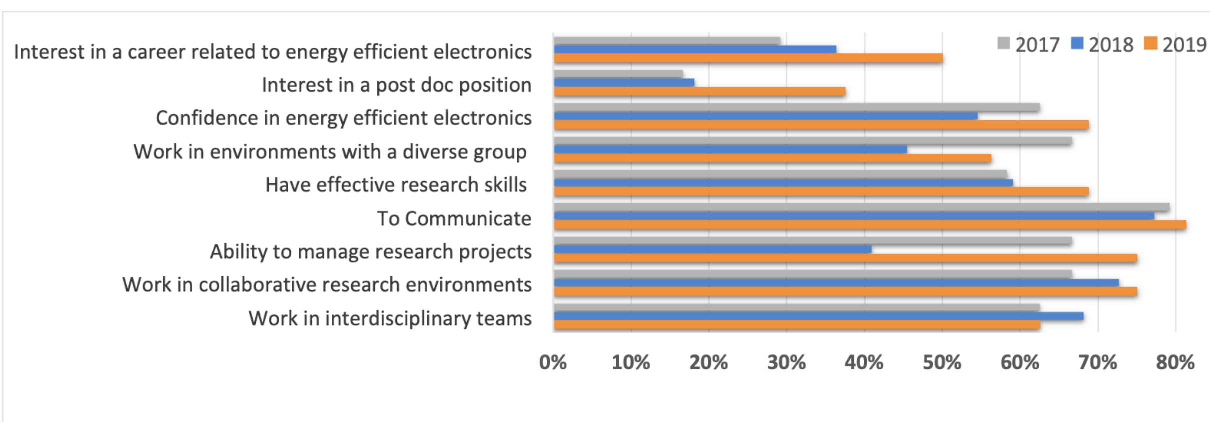

Figure 3.2. Graduate Students and postdocs indicated that the Center has positively impacted their professional development and interests.

The Center also manages two REU programs for undergraduates from four-year institutions and community colleges. Five community college students and six undergraduates from four-year institutions were hosted in E^3S or E^3S affiliated research groups at MIT and Berkeley. These programs boast demonstrated success in regards to community college transfer rates and pursuit of graduate studies (Table 3.1.). Additionally, in alignment with the Center's focus on community college education, five community college faculty members joined the Center in period 10 with the goal of enhancing STEM classroom instructions. These professors developed curriculum for courses in quantum computing, statistics, chemistry, biochemistry, biology, and physiology.

The following sections provide details supporting the above summary of the state of education in period 10.

2a. *Internal Educational Activities*

The internal educational activities that were initiated in previous reporting periods continued in period 10. 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^3S Research Seminars
Led by	**Michael Bartl** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total Summer 2019 attendance: 60 Faculty: 1 UTEP, 1 Berkeley Postdocs: 3 Berkeley Graduate Students: 12 Berkeley Undergraduates: 36 Berkeley Community college faculty: 3 Staff: 4

The E^3S 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. Speakers include graduate students, postdocs, faculty, and industry partners who present the progress of their research. During the academic year, the Center collaborated with the Department of Electrical Engineering and Computer Sciences to host six seminars. During Summer 2019, the Center hosted seminars; all were webcast to member institutions. The list of seminars speakers and topics 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	Eighth 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 – 63 Faculty: 8 Berkeley, 6 MIT, 1 UTEP, 1 FIU Postdocs: 7 Berkeley, 3 MIT, 1 Stanford Graduate Students: 19 Berkeley, 5 MIT, 2 FIU

	Undergraduate Students: 1 Consumes River College/UC Berkeley, 1 Columbia Industry Partners: 5

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, including an opportunity to present one's research at a poster session attended by representatives of member companies. There were 27 posters presented at the 2019 Annual Retreat, presented by 1 undergraduate student (Columbia), 19 graduate students (13 Berkeley, 1 FIU, 5 MIT), and 6 postdocs (5 Berkeley, 1 Stanford). Additionally, one community college student (Consumes River College) from the Transfer-to-Excellence REU was able to attend the retreat and present his research on carbon nanotubes. For a list of posters, please see Appendix G.

Table 3.4.

Activity Name	Annual Student and Postdoc Retreat (Focusing on Entrepreneurship)
Led by	**Nicole McIntyre** (Berkeley)
Intended Audience	Graduate Student and Postdoc Mentors
Approx. Number of Attendees (if appl.)	Total – 16 Graduate Students: 7 Berkeley, 1 FIU, 2 MIT Postdocs: 4 Berkeley, 1 Stanford Undergrads: 1 Columbia

In September, the Center hosted its 8th Annual Student and Postdoc Retreat for graduate students and postdocs. As part of the Center's objective to create future leaders, participants attended a entrepreneurship training. Caroline Winnett, Executive Director of SkyDeck, provided an overview of important aspects of entrepreneurship, available resources, and Berkeley SkyDeck, UC Berkeley's premier startup accelerator. Participants then engaged in discussion about common challenges and solutions when launching a business. E^{3}S students and postdocs then presented their entrepreneurship ideas to their peers and provided constructive feedback and recommendations. The E^{3}S Professional Development (PDP) program was discussed and recent awardees received their certificates.

Table 3.5.

Activity Name	E^{3}S 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: 2 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 paid research experiences to lower-division undergraduate students of member institutions. The major aim is to enhance the pipeline of students interested in graduate studies in the science and engineering disciplines of relevance to the Center. In period 9, two students participated in the ETERN program and were mentored by E^{3}S faculty and graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs such as research seminars.

To date, 86% (13) of ETERNS have completed a four-year degree in an E^{3}S related major and eight are currently enrolled in a graduate STEM program. Cumulatively, 40% (6) are underrepresented minorities and 33% (5) are female.

Table 3.6.

Activity Name	E^3S Rotation Program
Led by	**Michael Bartl** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 1 Graduate Students: 1 FIU

The Center enables its graduate students and postdocs to conduct research at a partner institution different from their own. During the summer of period 10, **Ingrid Torres** *(FIU)* spent her time doing research in Professor Jeffrey Bokor's lab at UC Berkeley. **Ingrid** was mentored by postdoc **Jyotirmoy Chatterjee.** Together, they worked on multilayered nanomagnetic structures for enabling multilevel 3D data processing.

2b. Professional Development Activities

The students and postdocs of the Center for E^3S have access to 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, received by students after completing enough areas in the Professional Development Program (E^3S PDP). This program prepares graduate students and postdocs with a diverse and balanced set of competencies.

Table 3.7.

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 – 39 Graduate Students: 22 Berkeley, 3 MIT, 2 FIU Postdocs: 9 Berkeley , 2 Stanford, 1 MIT

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. The E^3S PDP ensures 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, thirty-nine students and postdocs have earned a certificate of completion, of these, fourteen were awarded in Period 10. Seven of the graduate students and postdocs who graduated from the Center in period 10 have completed the PDP certificate and ten more members have only one training area remaining to complete the certificate.

Table 3.8.

Activity Name	Project Management and Mentor Training
Led by	**Nicole McIntyre and Kedrick Perry** (Berkeley)
Intended Audience	Graduate Student and Postdoc Mentors

Approx. Number of Attendees (if appl.)	Total – 20 Graduate Students: 12 Berkeley Postdocs: 8 Berkeley

As part of the Center's goal to provide leadership experiences, graduate students and postdocs who served as mentors in the Center's summer undergraduate research programs participated in project management and mentor training. Participants received two hours of mentoring and project management training, including 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.

Mentors then completed over 360 hours of hands-on practice in mentoring, supervisory skills, communication, and leadership. Qualitative analysis has found that serving as a Mentor in the Center's education programs enhances graduate students' and postdocs' skills in project management, supervision, teaching, and communication. These skills are important for members' future careers as faculty members, academics, and professional researchers. During period 11, Associate Director **Nicole McIntyre**, will be presenting these findings at the annual conference of the American Society for Engineering Education (ASEE).

Table 3.9.

Activity Name	REU Selection Committee
Led by	**Kedrick Perry** (Berkeley)
Intended Audience	All Graduate Student and Postdocs
Approx. Number of Attendees (if appl.)	Total – 8 Graduate Students: 6 Berkeley, 1 FIU, 1 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 materials, including personal statements, transcripts, and letters of recommendations of ~5 applicants. Based on their review process, the postdocs and graduate students provide a list of applicants that should be considered for placement in a REU summer research project.

2c. *External Educational Activities*

Providing educational activities to the wider campus communities, educators in community colleges, as well as STEM-interested students at the high-school and community college level is a major focus of the administrative team of the Center as well as all Center investigators (faculty, postdocs and students).

Table 3.10.

Activity Name	E^3S Course – EE 290B: Advanced Topics in Solid State Devices
Led by	**Eli Yablonovitch** (Berkeley)
Intended Audience	Graduate Students
Approx. Number of Attendees (if appl.)	Total – Graduate Students: 15 Berkeley

One of the Center's goals is to provide training in technical topics to both Center members and members of the public. As such, Center Director, **Eli Yablonovitch**, developed a UC Berkeley course titled "EE

290: Advanced Topics in Solid State Devices". This course covers the following topics: solid-state switching devices that operate in the milli-Volt regime, nano-transistor options with steeper sub-threshold slope, nano-optical links, novel nanoscale impedance matching transformers, including plasmonics, new forms of amplification using giant magneto-resistance and other spintronic effects, nanomechanical switching elements that are capable of very low voltage operation, low-temperature electronics, and electro-chemical switching elements. This course was first taught at the inception of the Center in Fall 2010 and is offered to members at all institutions through videoconferencing technology and online posting of course material. In period 10, 15 UC Berkeley graduate students enrolled, three of which were Center members.

Table 3.11.

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

Given 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 10, the Center hosted five community college faculty members who spent six to nine weeks developing curricula mentored by the Center's PI, **Eli Yablonovitch**. Leveraging a community faculty program that NSF awarded to the E^3S visiting faculty participated in a pedagogy workshop that taught community college faculty participants about context-based and online teaching. The five E^3S visiting community college faculty are described below.

- **Julieta Aguilar**, a faculty member in the Department of Biology at Los Angeles Trade Technical College (LATTC), one of the Center's education partners, developed course content for LATTC's first hybrid online and in-person "Introduction to Biology" course. The course was implemented in the Fall 2019 semester.
- **Leonard Filane**, a physics and math instructor at College of Marin, conducted nine weeks of curriculum development work to create a new quantum computing course. This was a continuation of the work he did in the previous three summers and he continues to work with Berkeley faculty and administrators to ensure the course is accredited for students to transfer to a four-year school.
- **Mahnaz Firouz** is a faculty member in the Science and Mathematics Department of Chabot College, Los Medanos College, Las Positas College, and Diablo Valley College. Dr. Firouz worked on preparing lectures and course materials for an "Introduction to Probability & Statistics" course that she had not taught before. She also spent time researching big data and data science in preparation for the two-year data science program being developed at Chabot College.
- **Carlos Rojo,** an instructor in the Biology Department at San Jose City College, spent his summer developing online modules of his Introduction to Physiology course. Carlos "flips" his lessons and classrooms to introduce higher level problem solving, discussion, and application in the classroom.
- **Kofi Opong-Mensah,** is a chemistry and toxicology instructor at various colleges including College of Marin, Los Medanos College, and the Contra Costa Community College District.

In Summer 2019, he worked on developing online courses for general chemistry and biochemistry classes.

Table 3.12.

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 38 Additional Co-authors

The E^3S E-book is a legacy material, conceived in period 7. The book will discuss E^3S research and be written at a high school or undergraduate level. Each research theme has a dedicated section within the book; theme leader have decided the subjects and chapters within each section. Graduate students and postdocs have continued to create content in period 10 and the Theme 2 section has been completed. At the end of Period 10, each theme will have produced a final draft of their section.

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: faculty mentor postdocs and graduate students, and postdocs and graduate students mentor undergraduates.

2e. *Performance Against Metrics*

During this reporting period, the Center has compared the educational programs with the period 10 targets. The table below displays these data and future metrics to measure education success.

Table 3.16.

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
Education	Center graduates completed E^3S training	P2: Baseline P3-5: 50% P6: 15% P7: 30% P8: 40% P9: 50% P10: 15%	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)	5 (36%)	3 (23%)	7 (58%)
	E^3S graduate students taking online course taught by Center director	P6, 8, 10: 0 P7, 9: 10	(new for P6-10)				0	8	0	6	3

Center for Energy Efficient Electronics Science

	Undergraduates who pursue advanced degree in science and engineering	P3: 5% P4: 30% P5: 35% P6: 40% P7: 45% P8-P10: 50%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)	36 (69%)	41 (73%)	47 (70%)	51 (71%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P2: Baseline P3: 5% P4-5: 80% P6-10: 85%	n/a	3 100%	6 100%	7 100%	6 100%	4 80%	4 60%	6 100%	6 100%
	Pre-college students who pursue a bachelor's degree in science and engineering	P3: Baseline P4-5: 70% P6-10: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)	180 (47%)	Program ended	
	Students and postdocs serving in leadership roles in the Center	P2: Baseline P3: 15% P4: 20% P5: 25% P6-8: 30% P9: 20% P10:15%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)	14 (16%)	17 (21%)	17 (25%)

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 11

Much of period 11 will be spent in continuing the established education programs and continuing in the creation and development of the Center's education legacy. The Center is expecting to have a final draft completed of the e-book by the end of the period and the video lecture series will be published.

One of the Center's REU programs is funded through period 11; additionally, the RET and ETERN program may also continue (funding dependent). Center staff will continue efforts to secure funding for these programs after the conclusion of the Center.

IV. KNOWLEDGE TRANSFER

1a. *Goals and Objectives*

As a Science and Technology Center, E^3S considers knowledge transfer activities and outcomes a key metric of its success. Indeed, knowledge transfer is at the heart of the Center for E^3S mission and vision to foster groundbreaking new science discoveries and fertilize new technologies. Consequently, knowledge transfer is seen as a two-way street at the Center for E^3S: Sharing its discoveries in the development of novel, highly efficient electronic technologies with various outside stakeholders, while bringing new knowledge into the Center by engaging with key players of various science and engineering disciplines and at different educational levels.

Since its inception, the Center has recognized establishing partnerships as a key factor in accelerating research, education and outreach endeavors, while, at the same time, the Center has put significant efforts into sharing new knowledge with industry, academia and research labs. In fact, the Center has continued to transfer knowledge to industry and seek input from our Industrial Research Board (Applied Materials, HP Enterprise, IBM, Intel, and Lam Research) and other companies the Center considers key players in low-energy electronics. Interactions occurred at multiple levels, including seminars by invited external speakers, Center students and postdocs visiting companies to learn about other low-energy electronics programs, and co-sponsorship of and participation in the BETR (Berkeley Emerging Technologies Research) Center's biannual meetings (see below in *Center Legacy Initiatives*).

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

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

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

1b. *Table 4.1. Performance Metrics*

Objective	Metrics	Frequency	Targets
Knowledge Transfer	Center publications	Yearly	Periods 2-5: Yearly: 18 Periods 6-7: 25 Periods 8-10: 30
	External citations of publications *(cumulative)*	Yearly	Period 3: 10 Period 5: 100 Periods 6-10: 25% yearly increase

	Talks at peer-reviewed conferences *(added in Period 6)*	Yearly	Periods 6-7: 12 Periods 8-10: 15
	Center sponsored symposia & workshops	Yearly	Period 2: baseline Period 3: 0 Period 4: 1 Period 5: 0 Period 6: 2 Periods 7-10: 1
	Website hits & unique visitors *(discontinued)*	Yearly	Period 2: Baseline Period 3: 20% increase
	Contacts with industry • Talks & Meetings • Presentations by industry	Yearly	 Periods 2-10: 36 Periods 2-10: 2
	Research Collaboration with industry	Yearly	Period 4: 1 Period 5: 2 Periods 6-7: 3 Periods 8-10: 4
	Patents Disclosures/Provisional	Yearly	Periods 3-4: 3 Period 5: 5 Periods 6-7: 2 Period 8: 3 Period 9-10: 4
	Patent Application Filed/Granted	Yearly	Period 4: 0 Period 5: 3 Period 6: 1 Periods 7-9: 2 Period 10: 3
	Center's alumni into relevant industries	Yearly	Period 5: 50% Periods 6-7: 30% Periods 8-9: 40% Period 10: 50%
	Center's alumni pursuing research in disciplines related to the Center at academia & research labs *(added in Period 6)*	Yearly	Periods 6-10: 30%
	Technology development attributable to Center's research • Low energy devices • Enabling other applications	Yearly	 Periods 6-7: 0 Periods 8-10: 1 Period 10: 2
	• Number of external articles on the Center *(discontinued)*	Yearly	Period 3: 100% increase Period 5: 50% increase

1c. *Problems Encountered*

Due to the departure of E^{3}S Associate Director of Education, **Lea Marlor**, in early May of this year, some of the education legacy projects have not been completed as originally planned for period 10; in particular, the launch of the E^{3}S *nanoHUB.org* website and the final edits to our educational videos. With the new Associate Director of Education, **Nicole McIntyre**, in place, these projects are again moving forward and we anticipate to launch the E^{3}S *nanoHUB.org* website including the educational videos by the beginning of period 11.

2a. Knowledge Transfer Activities in Period 10

The Center for E^3S has continued its wide range of knowledge transfer activities, including disseminating results and outcomes from research and education in journals, conference proceedings and lectures, by hosting visitors from the U.S. and internationally, by engaging various stakeholders (from academia to industry), by further developing the Center's legacy programs, and by using social media and other new platforms to reach a broad community of scientists and engineers, attract new students into the Center and reach out to the general public.

Dissemination of Results

Publications. The Center for E^3S prides itself in its strong dissemination record with high-impact publications and presentations. This trend has continued in period 10, broadly supported by all of the Center's researchers and key staff personnel through publications in high-impact scientific peer-reviewed journals, presentations at top national and international peer-reviewed conferences, scientific meetings, universities and industry, and knowledge exchange with a wide range of communities via public and private meetings. So far in this period, the Center has published 24 papers in journals, and additional six are under review. In addition, Center members presented 23 talks and 5 posters at scientific conferences and meetings.

Conferences. After five highly successful installments of the biennial Berkeley Symposium for Energy Efficient Electronic Systems, the Center for E^3S teamed up this year with the IEEE S3S Conference. This step was made to ensure that the Berkeley Symposium will live on in some form even after the sunset of E^3S—a stand-alone Berkeley Symposium would be impossible to organize without the full Center support. Combining the Berkeley Symposium with the IEEE S3S Conference (October 14-17, 2019, in San Jose, CA; http://s3sconference.org) was a natural choice since it covers many of the E^3S topics, and the Berkeley Symposium was already a 'satellite event' of the S3S Conference in 2015 and 2017. As part of the merger, six current and former E^3S senior investigators joined the S3S organization committee (**Eli Yablonovitch**, **Tsu-Jae King Liu**, **David Zubia**, **Farnaz Niroui**, **Eugene Fitzgerald**, and **Philip Wong**). We anticipate that the merger of the Berkeley Symposium with the world-renowned IEEE S3S Conference will create the premier gathering event for academia and industry to exchange the latest research results on energy-efficient circuits and devices, 3D Integration, and silicon on insulator technology.

Online, Social Media. The Center has continued to increase its presence in online content and social media—two increasingly important vehicles of knowledge transfer. The Center website (https://e3s-center.berkeley.edu/) was designed both to keep E^3S members informed on all Center aspects and to serve as a major recruiting tool for new students. The Center's social media presence (E^3S Twitter and Facebook sites) and its blog site further support recruiting and general outreach activities.

Center Legacy Initiatives

The Center for E^3S regards the development of a strong and lasting research and education legacy a key metric of success. Transferring the knowledge created in this Center for the next generation of engineers, scientists, and educators has been a high priority since the Center renewal in fall of 2015. E^3S prides itself on the educational and scientific influence it will continue to have on the future science and technology of energy efficient electronics. For example, the nanoelectronics theme has laid out the requirements for ultra-low power electronics that will guide future research, while the nanomechanics theme has demonstrated the importance of molecular functionalization on the surfaces of NEM switches that will likely become standard in the field of nanomechanics. The nanophotonics theme has shown that the antenna-LED is the missing link of optoelectronic sources for on-chip optical communication, and the nanomagnetics theme has shown the correct path for high-speed magnetic switching, increasing switching speed by 100 times, down to the picosecond range. Since the four different E^3S research themes represent different levels of technological maturity and will need to evolve separately, the E^3S leadership concluded that pursuing different paths for the different E^{3}S research themes is the most successful approach toward the development of strong and lasting legacy programs. Thus far, the Center has several continuing research initiatives and programs established and/or initiated:

Berkeley Emerging Technology and Research (BETR) Center. The BETR Center was established in 2016 with the goal to create a hub for physical electronics research at UC Berkeley. This Center is led by E^{3}S Nanomechnics Theme leader **Tsu-Jae King Liu** and E^{3}S Deputy Director **Jeffrey Bokor**, and is managed by Executive Director **Michael Bartl**. The BETR Center includes five additional E^{3}S investigators as members (**Eli Yablonovitch**, **Ali Javey**, **Sayeef Salahuddin**, **Vladimir Stojanović**, and **Ming Wu**) with the goal to form interactions with companies for long-term research collaborations and knowledge transfer. BETR is entirely funded by company members ("industrial affiliates"). These corporate sponsors gain early access to innovative ideas and research results, while university researchers gain insight into challenges faced by industry. Current BETR industry members include Applied Materials, Atomera, Lam Research, Futurewei, TSMC, and Texas Instruments. During this funding period, the Center organized two workshops (details are given in Appendices H and I).

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

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

Semiconductor Research Corporation (SRC) JUMP Centers. Of the six current SRC JUMP Centers, E^{3}S investigators are part of two centers: ASCENT (Applications and Systems driven Center for Energy-Efficient Integrated NanoTechnologies) and ComSenTer (Center for Converged TeraHertz Communications and Sensing). **Jeffrey Bokor**, **Sayeef Salahuddin**, and **Shan Wang** are part of the ASCENT Center, working on spintronic switching, whereas **Vladimir Stojanović** and **Alon Elad** are members of the ComSenTer Center, focusing on high-speed circuits and systems.

E^{3}S e-Book and nanoHUB Website. At the beginning of this period, the Center for E^{3}S established its own website on the nanoHUB.org platform. Currently, content is produced and we expect the site to go live early next year. Highlights of this site will include educational videos featuring Center research topics targeting various educational levels (from high school to graduate level). In addition, the site will host the E^{3}S open-access e-book on energy efficient electronics written by E^{3}S faculty, postdocs and students. The objective of the e-book is to develop a comprehensive educational resource on energy efficient electronic science (including nanoelectronics, nanomechanics, nanophotonics, and nanomagnetics) to motivate high school students to pursue academic studies and careers in the STEM fields.

TTE Renewal Grant and Third-Party Support. The Transfer-to-Excellence (TTE) Research Experience for Undergraduates (REU) program was developed in the Center for E^{3}S with the goal to reach out to students at the California Community College (CCC) system. This program was so successful that NSF provided additional funding through a separate REU grant that expanded the research topics to various areas in engineering and science. This program is now in its third generation (i.e. two successful grant renewals) and will enable E^{3}S to continue the TTE REU program beyond the sunset of the Center for E^{3}S (in 2020). In addition, other Centers on the Berkeley campus have implemented the TTE REU concept in their educational programs. For example, for the last two summers the Center for E^{3}S has integrated up to five students annually from an NIH-funded center (PI Doudna) into its TTE program. Finally, E^{3}S is delighted to report that in October of this year, the Center for E^{3}S, in conjunction with the UC Berkeley Department of Electrical Engineering and Computer Sciences, received a $400,000 grant from the Hopper-Dean Foundation to expand the TTE REU program for ten computer science majors per year.

Details of E^{3}S Knowledge Transfer Activities

- *Dissemination of Results*

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

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

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

So far in this reporting period, the Center's faculty, postdocs, students, and staff have published 30 papers (including six submitted manuscripts), all in peer-reviewed journals (excluding peer-reviewed conference proceedings). An important performance metric included in the Strategic Plan is the number of citations of the Center's publications. By the submission of this report the cumulative citation count for the 209 published journal papers of the Center was 9447, an increase of 55 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.	Stanford	Palo, CA

So far, four talks by E^{3}S member institutions were published in conference proceedings.

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

Led by	**Kedrick Perry, Nicole McIntyre**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	McNair Symposium	Los Angeles, CA
4.	International Materials Research Symposium	Cancun, Mexico
5.	SACNAS Annual Conference	Honolulu, HI
6.	Gulf Coast Undergraduate Research Symposium	Houston, TX
7.	Society for Women Engineers Conference	Anaheim, 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 10, the following conferences each had one E^3S REU alumni student presenter: McNair Symposium in July/August in Los Angeles, International Materials Research Congress in August in Cancun (Mexico), SACNAS Conference in October/November in Hawaii, Gulf Coast Undergraduate Research Symposium in November in Houston, and Society of Women Engineers Conference in November in Anaheim.

Table 4.5. Granted Patents & Patent Applications

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

So far, in period 10, four new patents have been granted to E^3S researchers at *Berkeley*, *MIT* (2) and *FIU* (two each from Themes II and IV). In addition, two new invention disclosures have been filed (UC Berkeley and MIT; Themes I and IV).

Table 4.6. 2019 IEEE S3S Conference (including the Berkeley Symposium)

Led by	**Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	UTEP	El Paso, TX
4.	Stanford	Palo Alto, CA
5.	IEEE S3S Conference Organization	San Jose, CA

The Center for E^3S teamed up this year with the IEEE S3S Conference and integrated the Berkeley Symposium for Energy Efficient Electronic Systems with the S3S event. The IEEE S3S Conference was held October 14-17, 2019, in San Jose, CA (http://s3sconference.org) with six current and former E^3S senior investigators joining the S3S organization committee: **Eli Yablonovitch** and **Tsu-Jae King Liu** (both *Berkeley*), **David Zubia** (*UTEP*), **Farnaz Niroui** and **Eugene Fitzgerald** (both *MIT*), and **Philip Wong** (*Stanford*). The merger was managed and coordinated by E^3S Executive Director **Michael Bartl** (*Berkeley*).

Table 4.7. Partnership with University of Twente

Led by	**Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	University of Twente	Twente, Netherlands

The Center for E^3S hosted 26 applied physics/engineering students and two professors from the University of Twente (Netherlands) for a one-day visit on July 16, 2019. The goal was to explore future research collaborations and student exchange possibilities with the University of Twente. The visit featured overview presentations of the Center for E^3S (**Michael Bartl**), the Berkeley graduate admission process (**Nicole McIntyre** and **Kedrick Perry**), and the Berkeley Marvell NanoLab (**Allison Dove**). In addition, E^{3}S students and postdocs organized a joined lunch and campus walking tour. The visit agenda is given as Appendix J.

Table 4.8. Partnership with California Engineering Liaison Council

Led by	**Nicole McIntyre**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	California Engineering Liaison Council	Twente, Netherlands

The Center co-sponsored the fall meeting of the *California Engineering Liaison Council at UC Berkeley.* The Engineering Liaison Council (ELC) is the one organization in California that networks all institutions of higher learning engaged in engineering education. At the meeting, faculty members from various institutions exchanged best practices and discussed how to further cooperation. The Council aims to educate a diverse and skilled engineering workforce that can continue to place California in the forefront of technology. During the two-day meeting in October 2019, Center Faculty Director of Education **Tsu-Jae King Liu** gave a welcome address and Center Associate Director **Nicole McIntyre** presented on the Transfer-to-Excellence REU program. The meeting agenda can be found in Appendix K.

Table 4.9. Partnership with California State University, Los Angeles

Led by	**Kedrick Perry**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	California State University, Los Angeles	Los Angeles, CA

Under the leadership of E^{3}S diversity director, **Kedrick Perry**, the Center hosted 20 students and faculty members from the California State University, Los Angeles for a one-day visit on June 26, 2019. The visit included a campus walk, research presentations for students and presentations about the Berkeley graduate admission process.

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

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

Table 4.10. RIE process with Digital Etch Technology for III-V High Aspect Ratio Features

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

Developed for III-V nanowires, as part of Theme I's TFET research, the REI digital dry etch technology has found great use in other research programs in the **del Alamo** group. This technology has proven to be transformational. Excellent device results have demonstrated the potential of III-V MOSFETs for future CMOS.

Table 4.11. Exploring the Limits of Vertical-Nanowire Tunnel FETs in the Nanoscale

Led by	**Jesus del Alamo**	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	Intel Corporation	Hillsboro, OR

The III-V nanowires were originally developed in the del Alamo group as part of Theme I's TFET research. This technology has garnered great interest from industry since excellent device results have demonstrated the potential of III-V MOSFETs for future CMOS.

Table 4.12. Magnetoelectric Nanoparticles for Batteries

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

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

Table 4.13. Negative Capacitance Transistors

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

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

Table 4.14. Graphene Nanoribbon TFETs

Led by	**Jeffrey Bokor, Felix Fischer**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	TSMC	San Jose, CA (Headquarters: Taiwan)

E^3S Deputy Director **Jeffrey Bokor** and E^3S senior investigator **Felix Fischer** have a research contract with TSMC to fabricate graphene nanoribbon based TFET devices (originally developed in the E^3S nanoelectronics theme).

Table 4.15. Intel Board of Directors

Led by	**Tsu-Jae King Liu, Jeffrey Bokor, Michael Bartl**	
Organizations Involved		
	Name	*Address*

1.	UC Berkeley	Berkeley, CA
2.	Intel Corporation	Hillsboro, OR

E^3S Nanomechanics Theme leader **Tsu-Jae King Liu** is a member of the Intel Board of Directors.

Table 4.16. Berkeley Emerging Technologies Research (BETR) Center

Led by	**Tsu-Jae King Liu, Jeffrey Bokor, Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	TSMC	San Jose, CA (Headquarters: Taiwan)
3.	Applied Materials	Santa Clara, CA
4.	Texas Instruments	Dallas, TX
5.	Futurewei	Santa Clara, CA
6.	Atomera	Los Gatos, CA
7.	Lam Research	Fremont, CA

The BETR Center was established in 2016 with the goal to create a hub for physical electronics research at UC Berkeley. This Center is led by E^3S Nanomechnics Theme leader **Tsu-Jae King Liu** and E^3S Deputy Director **Jeffrey Bokor**, and is managed by Executive Director **Michael Bartl**. The BETR Center includes five additional E^3S investigators as members (**Eli Yablonovitch**, **Ali Javey**, **Sayeef Salahuddin**, **Vladimir Stojanović**, and **Ming Wu**) with the goal to form interactions with companies for long-term research collaborations and knowledge transfer. BETR is entirely funded by company members ("industrial affiliates"). During this period, the Center organized two workshops (details are given in Appendices H and I).

- *Knowledge Transfer into the Center*

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

Table 4.17. 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

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

Table 4.18. Seminars by Invited Speakers

Led by	**Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	Lam Research	Fremont, CA
2.	Harvard University	Cambridge, MA
3.	Duke University	Durham, NC
4.	UC Merced	Merced, CA
6.	UC Berkeley	Berkeley, CA
7.	MIT	Cambridge, MA
8.	Stanford	Palo Alto, CA
9.	UTEP	El Paso, TX
10.	FIU	Miami, FL

In period 10, select seminars from external speakers of the BETR/Solid State seminar series have again been co-sponsored by E^3S, including **Sadasivan Shankar** (*Harvard*), **Jelena Notaros** (*MIT*), **Natalia Litchinitser** (*Duke*), **Eric Pop** (*Stanford*), and **Sarah Kurtz** (*UC Merced*). In addition, the Center invited **Nerissa Draeger** from our industrial partner *Lam Research* again to present a seminar to our summer undergraduate REU students. More details about seminars can be found at *https://e3s-center.berkeley.edu/news-events/seminars/*.

Table 4.19. Student Visit of Joint BioEnergy Institute Research Facilities

Led by	**Nicole McIntyre (UC Berkeley)**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Joint BioEnergy Institute Research Facilities	Emeryville, CA

Summer REU program participants were able to visit the Joint BioEnergy Institute (JBEI) research facilities this summer. The visit was coordinated by E^3S Education Director, **Nicole McIntyre**, and **Irina Nogueira Da Silva** from *JBEI*. Students also had the chance to speak to representatives of JBEI and learn about the Institute's goal and scientific process. The visit took place on July 15, 2019, and also included a tour of the laboratories and a career discussion (see Appendix L).

Table 4.20. REU Student Visit of UC Davis Graduate School Event

Led by	**Nicole McIntyre**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	UC Davis	Davis, CA

Part of the TTE REU program is a visit of a different University of California (UC) campus, other then Berkeley, to give students a wider prospective of the UC system. This year, we were invited by UC Davis to their Graduate Scoop event, where prospective graduate students from predominantly underrepresented groups learn about preparing and applying to graduate school, get a tour of the campus, labs or programs, and hear from professionals about the graduate application and how to finance your graduate education. The event took place on July 20, 2019, and was coordinated by E^3S Education Director, **Nicole McIntyre**.

Table 4.21. Student Visit of Lam Research Facilities

Led by	**Kedrick Perry, Nicole McIntyre**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Lam Research	Fremont, CA

For a third time in a row, this summer, we were fortunate again to be invited back by Lam Research for a visit by our graduate students and the summer REU student cohort. This year's visit of the Lam Research headquarters in Fremont, CA, took place on July 22, 2019 and was coordinated by E^3S Diversity Director, **Kedrick Perry**, Education Director, **Nicole McIntyre**, and **Nerissa Draeger** from *Lam Research*. The visit included a tour of the manufacturing units, including the impressive cleanroom facilities. Students also had the chance to speak to representatives of Lam Research.

- *Education Knowledge Transfer*

  The Center for E^3S was again present at the most important national education and diversity events, and continued its fruitful interactions with the broader community. Doing so, education associate director **Nicole McIntyre** and diversity director **Kedrick Perry** engaged in knowledge transfer through written and oral dissemination of best practices, curriculum development and dissemination, and in-person outreach. In detail, E^3S participated in six education, diversity and recruiting conferences, including the Collaborative Network for Engineering and Computing Diversity (CoNECD) Conference by the American Society for Engineering Education (ASEE), the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) Conference, the Mathematics, Engineering, Science, Achievement (MESA) Conference, the California Engineering Liaison Council Fall Meeting, the NSF EEC Grantees Conference, and the National Association of Diversity Officers in Higher Education Annual Conference. In addition, E^3S TTE REU student Safi Mohammed attended the SACNAS Meeting and won the Best Engineering Poster Award for his research project on "Surface Synthesis and Dry-Transfer of Graphene Nanoribbons for High-Performance Field Effect Transistors".

  In October 2019, Deputy Center Director & Faculty Director of Diversity, **Jeffrey Bokor**, attended Rising Stars in EECS at MIT and served as a Mentor for participants seeking career advice and feedback on technical job talks. This event is an intensive workshop for women graduate students and postdocs who are interested in pursuing academic careers in electrical engineering and computer science. The UC Berkeley Department of Electrical Engineering & Computer Sciences will be hosting the event in 2020.

2b. Outcomes

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

2c. *Table 4.16. Performance Against Metrics*

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
Knowledge Transfer	Center publications	P2-5: 18 P6-7: 25 P8-P10: 30	22	21	27	48	39	36	33	33	32 (6 subm)
	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26	21	22
	Center sponsored symposia & workshops	P2: Baseline P3: 0 P4: 1 P5: 0 P6: 2 P7-9: 1 P10: 2	1	0	1	0	1	1	2	2	2
	External citations of publications *(cum)*	P3: 10 P4-5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase	6076 40% increase	9447 55% increase
	Industry contacts:										
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38	41
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8	7	7
	Patent disclosures										
	• Disclosure/ Provisional	P3: 3 P4: 3 P5: 5 P6: 2 P7: 2 P8: 3 P9-P10: 4	1	0	1	0	2	1	4	0	4

	• Patent/Patent Application	P4: 0 P5: 3 P6: 1 P7-P9: 2 P10: 3	1	2	1	3	8	4	1	2	2
	Technologies attributable to Center's research										
	• Low energy devices	P6-P9: 0 P10: 1	(new for P6-10)				0	0	0	0	0
	• Enabling other applications	P6-7: 0 P8-P9: 1 P10: 2					0	0	0	1	1
	Center's alumni into relevant industries	P5: 50% P6-7: 30% P8-P9: 40% P10: 50%	Student 0% Postdoc 100% (1)	Student 64% (7) Postdoc 33% (2)	Student 16% (2) Postdoc 20% (2)	Student 16% (6) Postdoc 40% (4)	Student 50% (12) Postdoc 13% (1)	Student 22% (2) Postdoc 18% (2)	Student 33% (4) Postdoc 60% (3)	Student 22% (2) Postdoc 0	Student 38% (3) Postdoc 67% (4)
	Center's alumni pursuing research in academia & research labs in disciplines related to the Center	P6-10: 30%	(new for P6-10)				Student 38% (9) Postdoc 88% (7)	Student 78% (7) Postdoc 82% (9)	Student 58% (7) Postdoc 40% (2)	Student 56% (5) Postdoc 83% (5)	Student 50% (4) Postdoc 33% (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 11

The defining goal for knowledge transfer activities in period 11 of the Center for E^3S will be to further extend and strengthen an impactful and lasting legacy while continuing its current broad knowledge transfer program. On the educational knowledge transfer side, the goal will be to launch the E^3S *nanoHUB.org* website and post educational videos, which will be available to a wide audience from high school to graduate student level. Furthermore, E^3S plans to publish its open-access e-book on energy efficient electronics by the end of period 11.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

Collaborations and partnerships are an integral part of the mission of the NSF Science and Technology Center for E^3S. Indeed, developing new partnerships and nurturing existing ones has been a major aim of the Center since its inception. In the last nine years, E^3S has built a large number of formal and informal external partnerships with industry, national labs, policy makers, and educational institutions. These partnerships have spanned all aspects of Center activities, from research, to education, knowledge transfer and broadening participation.

As discussed below in Performance Metrics (section 1b), 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 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 education and diversity programs of the Center 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, which are described in detail in section III "Education" and section IV "Diversity" of this Annual Report.

In terms of external research partnerships, the Center has continued to execute and enhance its partnership strategy in period 10 to enable successful achievement of all its goals.

1b. Performance Metrics

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

As in past reporting periods, the Center will continue to track the number of contacts with industry in two categories: a) talks given to and meetings with industry, and b) 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 10

The Center has continued to engage industry partners to accelerate research and knowledge transfer. This has been achieved mainly in two ways: 1) Participation as a member in the E^3S Industrial Research Board, and 2) membership as an industrial affiliate in the Berkeley Emerging Technologies Research (BETR) Center—the prime research legacy establishment of E^3S.

- Participation as a member in the E^3S Industrial Research Board has continued to be a 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. In addition to 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 10, two of the five member companies had additional engagement with the Center beyond an advisory level.
  - *Lam Research*
    - **Jesus del Alamo** (*MIT*) has a continued partnership with Lam Research on the high aspect ratio digital etch technology for broader semiconductor applications.
    - Executive director **Michael Bartl** (*Berkeley*) was an invited participant in this year's the Lam Technical Symposium.
  - *Intel Corporation*
    - Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) is an elected Board of Directors member at Intel Corporation.
    - **Jesus del Alamo** (*MIT*) started a research partnership with Intel on exploring the limits of vertical-nanowire TFETs in the nanoscale.

- In the last two periods, the Berkeley Emerging Technologies Research (BETR) Center has emerged as the prime research legacy establishment of E^3S. As described in section IV (Knowledge Transfer), BETR is a hub for physical electronics research at UC Berkeley with the goal to form interactions with companies for long-term research collaborations and knowledge transfer. BETR is entirely funded by company members ("industrial affiliates"). Current BETR industry members include Applied Materials, Atomera, Lam Research, Futurewei, TSMC, and Texas Instruments. In Period 10, three member companies had directed research projects with E^3S senior investigators:
  - *Texas Instruments* and *Atomera*
    - Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) collaborates with Texas Instruments and Atomera on projects about SegFET transistor technology for RF applications.
  - *TSMC*
    - Deputy director **Jeffrey Bokor** and Theme I investigator **Felix Fischer** (both *Berkeley*) have a joined research project with TSMC on the development of graphene nanoribbon transistors.

- Other companies work with the Center in focused and limited manner.
  - **Jing Kong** (*MIT*) had multiple visits and research discussions about joint projects with TSMC.
  - Former E^3S investigator **Philip Wong** (*Stanford*) is now a vice president at TSMC.

In this period, 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. **Nerissa Draeger**, the main Lam Research contact for E^3S, also came to Berkeley to present a seminar to E^3S students.

The Center developed a partnership with the University of California at Davis, and E^3S undergraduate summer students participated in the Davis Graduate Scoop event. This event is directed toward prospective graduate students from predominantly underrepresented groups with the goal to learn about preparing and applying to graduate school, get a tour of the campus, labs or programs, and hear from professionals about the graduate application and how to finance your graduate education.

In period 10, the Center engaged in a new international partnership with the University of Twente (Netherlands). As part of this partnership, E^3S hosted 26 applied physics/engineering students and two professors from the University of Twente with the goal to explore future research collaborations and student exchange possibilities. The visit featured overview presentations of the Center for E^3S, the Berkeley graduate admission process, and the Berkeley Marvell NanoLab. A highlight was a walking tour of the Berkeley campus (including campanile visit) organized by E^3S students and postdocs.

The above discussions of partnership activities are not intended to be inclusive of all partnerships. A summary list of all partners is given in the Centerwide Output section of this report.

2b. Outcomes and Impact

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

2c. Performance Against Metrics

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
	Industry contacts:										
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38	41
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2	2
	Research collaboration with industry	P4: 1 P5: 2 P6: 3 P7: 3 P8-P10: 4	0	1	1	4	6	8	8	7	7

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

2d. Partnerships Plans for Period 11

While the Center for E^3S is sun-setting, we fully expect that we the emerging of the legacy BETR Center, existing research partnerships with industry will continue in and beyond period 11 and new ones will be formed as opportunities arise.

Similarly, we expect main E^3S external education partnerships to continue past the life of the Center. In fact, funding for the E^3S signature educational program, the TTE REU, has been secured for at least two more years (NSF grant and Hopper-Dean Foundation award). In addition, the Center will continue to seek new 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 STEM fields.

VI. DIVERSITY

1a. Goals and Objectives

To enable the vision of contributing to a diverse STEM workforce, the Center for E^3S strives to broaden participation by recruiting and retaining individuals from groups traditionally underrepresented in the disciplines represented in the Center. Moreover, E^3S aims to foster their development and aid them in the transition to scholars, researchers, or members of the STEM workforce. In particular, the Center focuses on participation by those who may identify as underrepresented based on their racial/ethnic group, gender, LBGTQ status, veteran status, first-generation status, socioeconomic status, and difference in ability.

With the goal of broadening participation within E^3S 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^3S research. Furthermore, E^3S cultivates an inclusive environment that embraces, and encourages intellectual curiosity and socio-cultural development.

The Center infuses equity and inclusion throughout its programmatic endeavors to enhance both the academic experience and the scholarly environment to prepare students to enter an increasingly complex and diverse society. Since the inception of the Center for E^3S, 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 10, 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. Also, acknowledging that diversity funding is being phased out in the sun-setting period, the leadership team has worked to ensure the diversity legacy lives on in the many students who are in grad school and beyond.

In period 10, the Center aimed to increase diversity by participating in several recruiting events across the nation. This year, **Nicole McIntyre**, attended STEM diversity annual conferences and visited eight 2-year colleges to recruit students for the community college program. Additionally, five online information sessions were hosted for students from other community colleges. 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. **Nicole McIntyre** also attended the California Engineering Liaison Council Conference, MESA Student Leadership Conference, and Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Diversity in STEM conference to recruit participants for the Center's programs. E^3S also had representation at the American Indian Science and Engineering Society (AISES), Out in STEM (OSTEM) and plans to have a presence at 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 10, **Kedrick Perry** once again gave a talk incorporating concepts of diversity. This year's talk focused on issues of diversity, equity and inclusion seen in the political sphere.

1b. Table 6.1. Performance Metrics

Objective	Metrics	Frequency	Targets
Diversity	Women in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 30%

			Period 5: 20% Periods 6-10: 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% Periods 9-10: 15%
	Participants from underrepresented* groups in the Center's Diversity programs	Annually	Period 3: Baseline Period 4: 80% Period 5-10: 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% Periods 8-10: 50%
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate *(new)*	Annually beginning in Period 6	Period 6-10: 85%
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering *(new)*	Annually beginning in Period 6	Period 6-10: 80%

1c. Problems Encountered

In period 10, the Center has still been challenged by the lower than optimal number of women and underrepresented minorities at the graduate student level. The Center has remained diligent in its efforts to increase the number of these two groups; however, a significant increase has been slow. One reason for the slow progression is the difficulty of transitioning undergraduate students from the Center's research programs (i.e., REU and E^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, E^3S leadership is working with departments and colleges of all partner institutions to transfer many of the successful diversity efforts and programs.

2a. Development of US Human Resources

In period 10, 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 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*

While the Center will continue his close ties with the MIT Online Science, Technology, and Engineering Community (MOSTEC) program, the reduced budget in the E^3S sun-setting period did not allocate new funds to MOSTEC. The Center is grateful to have been a partner of this exciting and impactful program.

- *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	**Nicole McIntyre** (Berkeley) and **Jeffrey Bokor** (Berkeley)
Intended Audience	Community college students
Approx. Number of Attendees (if appl.)	Total: 5 URMs: 3 (60%), First Gen: 3 (60%); Pell Grant recipients: 4 (80%)

During summer 2019 (Period 10), E^3S at UC Berkeley hosted three of fifteen community college students in the TTE REU program. These students completed nine weeks of research in the laboratories of E^3S faculty, **Ming Wu**, **Jeffrey Bokor,** and **Sayeef Salahuddin**; and E^3S 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.

In Period 10, 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 **Nicole McIntyre.** For details on enrichment activities, see https://e3s-center.berkeley.edu/wp-content/uploads/2019/09/2019-Program-Calendar.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, 94% (97) of the TTE program 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, 88% (86) enrolled at a UC campus;

60% (59) enrolled at UC Berkeley, and 88% (86) 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. In Period 10, the Center is also researching the positive effects of mentoring relationships on the graduate students and post-docs who serve as Mentors in the program.

Upon renewal of the TTE REU Site grant in period 9, an online mentoring program was planned to follow the conclusion for REU participants. This program in intended to facilitate a long-term, sustained and formalized mentoring relationship between all participants and a graduate student or post-doc mentor. And debuted in August 2019 with all four of the intern and mentor pairs participating. Each month, the Mentor/Mentee pair discusses a strategic and structured prompt in-person, via skype, or in-person (when possible). The program objectives are to (1) support participants through the application and selection process to a four-year baccalaureate institution, (2) encourage participants' pursuit of future undergraduate research opportunities, (3) retain and further stimulate participants' interest in graduate school, and (4) continue to help guide participants in their career choices.

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 and MIT. The primary goal is to attract undergraduate students, particularly those from groups underrepresented in science and engineering, to the Center's research in energy efficient electronics science, and graduate studies in science and engineering at the Center's member institutions.

Table 6.4

Activity Name	E^{3}S Research Experiences for Undergraduates at Berkeley & MIT (E^{3}S REU)
Led by	**Kedrick Perry** (Berkeley) and **Eli Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx. Number of Attendees (if appl.)	Total: 6 Female: 3 (50%), URMs: 2 (33%)

The Center's 9-week E^{3}S REU program received 70 applications. Five of these students were matched with Center faculty at Berkeley and one at MIT. At MIT, our student was hosted by **Jesus del Alamo**. At Berkeley, students were hosted by E^{3}S faculty, **Tsu-Jae King Liu**, **Ali Javey**, **Eli Yablonovitch**, and **Ming Wu.** 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. Calendar of events and activities: https://e3s-center.berkeley.edu/wp-content/uploads/2019/11/2019-E3S-REU-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.

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 10, the Center targeted students at institutions that may not offer, or have limited offerings in, courses and research on energy efficient electronics science.

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

For the community college programs, **Nicole McIntrye** visited several community colleges with plans to visit more in January. 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 10, the Center has committed available resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. E[3]S believes active recruitment ensures that all programs will have access to competitive candidates and highly qualified participants, regardless of race, color, or gender. As a result, 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 10 even as the Center sunsets. The Center leveraged existing partnerships with nationally recognized pre-college and higher education programs and has formed new alliances to collectively tackle the challenge of building a diverse pipeline of students who will eventually contribute to a diverse workforce.

2c. Table 6.5. Performance Against Metrics

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
Diversity	Women in the Center's research programs	P2: Baseline P3: 5% P4: 30% P5: 20% P6-10: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)	12 (14%)	20 (23%)	18 (16%)
	Underrepresented minorities in the Center's research programs	P2: baseline P3: 15% P4: 5% P5-6: 10% P7-8: 12% P9-10: 15%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)	11 (13%)	15 (17%)	11 (15%)
	Participants from under represented*	P3: Baseline P4: 80%	n/a	n/a	Women 37 (44%)	Women 26 (41%)	Women 29 (40%)	Women 25 (40%)	Women 38 (44%)	Women 40 (42%)	Women 40 (35%)

Center for Energy Efficient Electronics Science

	groups in the Center’s Diversity programs	P5-10: 85%			URMs 58 (68%)	URMs 36 (56%)	URMs 49 (67%)	URMs 38 (60%)	URMs 48 (55%)	URMs 50 (58%)	URMs 45 (64%)
				Total 93 (82%)	Total 73 (86%)	Total 49 (77%)	Total 66 (90%)	Total 63 (87%)	Total 69 (80%)	Total 68 (77%)	Total 70 (79%)
	Undergraduate participants from under-represented* groups pursuing advanced degrees in disciplines related to the Center	P6: 40% P7: 45% P8-P10: 50%	(new for P6-10)				17 (55%)	23 (54%)	27 (50%)	30 (55%)	32 (53%)
	Community College students from under-represented* groups pursuing a science or engineering baccalaureate	P6-10: 85%	(new for P6-10)				16 (70%)	22 (81%)	24 (80%)	30 (88%)	36 (90%)
	Pre-college participants from under-represented* groups pursuing a bachelor in science or engineering	P6-10: 80%	(new for P6-10)				73 (55%)	102 (63%)	14 (33%)	Program ended	

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 11

Due to the reduction of diversity funds and as the Center sunsets, Diversity Director, **Kedrick Perry**, will not be with the Center in 2020, and all education and diversity efforts will be directed by Associate Director for Education, **Nicole McIntyre**. E^3S will focus on maintaining and strengthening its 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 through the TTE REU program. **Kedrick Perry** will continue to champion diversity, equity, and inclusion during the rest of his tenure with the Center.

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 departure of **Lea Marlor**, Associate Director for Education, from the Center and the Executive Committee in April 2019, (2) the addition of **Nicole McIntyre** to replace Lea Marlor as Associate Director of Education and member of the Executive Committee in May 2019. Lea Marlor decided to go back to graduate school and joined the Ph.D. program in engineering education at the University of Michigan. Nicole McIntyre came to E^3S from UC Berkeley's EECS Department where she was Lead Adviser & Program Coordinator in the Undergraduate Affairs Office. After starting her roles as Associate Director of Education and member of the Executive Committee in the Center for E^3S, she successfully managed all summer TTE and RET programs fully independently.

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 Bulović – 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 (March 1 – April 30, 2019)
      - Nicole McIntyre – Associate Director of Education (May 21, 2019 – Present)
      - Kedrick Perry – Director of Diversity and Outreach
    - ii) Elected members:
      - David Zubia, University of Texas at El Paso (UTEP)
  - b) The nine-member executive board was ratified on July 11, 2019 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 on July 11, 2019 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, a part-time program assistant, and various student assistants. Executive director Michael Bartl is also directing the signature research legacy program of E^3S, the Berkeley Emerging Technologies Research (BETR) Center, an industry-funded center focussed on solid state engineering and technology solutions. More details about the BETR Center are given in section IV (Knowledge Transfer).
  - The Center's programmatic efforts in education and diversity are the responsibility of the associate director of education and the director of diversity and outreach. As has been the case

since the start of the Center, the education and diversity programs enjoy faculty support through the two faculty director positions, which are currently held by **Jeffery Bokor** (faculty director for diversity) and **Tsu-Jae King Liu** (faculty director for education).

1b. Table 7.1. Performance Metrics

Objective	Metrics	Frequency	Targets
Center Management	Centerwide Communications *(discontinued)*		
	Annual Surveys:		
	• Students /Postdocs	Annually	According to Likert scale: Periods 2-5: 3 or higher Periods 6-10: 4 or higher
	• Co-PIs	Annually beginning in Period 3	
	• External Advisory Board	Annually	
	Authorship disputes	Annually beginning in Period 3	Periods 2-5: 20% decrease Periods 6-10: 0
	Plagiarism	Annually	Periods 2-10: 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

The Center leadership has continued to periodically seek feedback from all Center participants (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 the Center's external evaluator, **Catherine Amelink**. The external evaluator reports the result of the surveys (with all names and personal information removed) to the E^3S leadership team.

Table 7.2. Center Management Metrics Table

Category	Metric	Targets	Results								
			P2	P3	P4	P5	P6	P7	P8	P9	P10
Center Management	Annual Surveys (measured and reported on Likert Scale)										
	• Students /Postdocs	P2-5: 3 or higher P6-10: 4 or higher	3.9±0.2	4.0±0.3	4.2±0.2	4.5±0.2	4.3±0.2	4.3±0.3	4.4±0.1	4.3±0.2	4.6±0.3
	• Co-PIs		No survey	Leader-ship 4.46	Leader-ship 4.7±0.5	Leader-ship 4.9±0.1	Leader-ship 4.6±0.1	Leader-ship 4.8±0.2	Leader-ship 4.8±0.1	Leader-ship 4.8±0.1	Leader-ship 4.6±0.1
	• External Advisory Board		Strategic Plan: 4.2 Center Status 4.0	Strategic Plan: 4.1 Center Status 4.0	Strategic Plan: 4.6 Center Status 4.6	Strategic Plan: 4.4 Center Status 4.7	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	Center Legacy 4.8±0.4	N/A
	Authorship disputes	P2-5: 20% decrease P6-10: 0	0	0	0	0	0	0	0	0	0
	Plagiarism	P2-10: 0	0	0	0	0	0	0	0	0	0
	Changes in Center processes made in response to evaluation results	3 months for closure of regular action; 1 week for closure of time-sensitive action	(new for P6-10)				0	0	0	0	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.*

As has been done in previous years, two center-wide perception surveys were conducted: 1) Postdocs and graduate student survey (see also Appendix M) and 2) faculty survey (see also Appendix N). Period 10 has been the ninth year in which the graduate students & postdocs survey has been conducted. The faculty and the postdoc/student surveys both resulted in overall average leadership ratings of 4.6 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.

It should be noted that a score of 4.6 on the Likert scale is impressively high. The only student and postdoc survey question receiving a score lower than 4.0 was the questions “Since joining the Center I have developed a working relationship with someone in the Center who is not part of my home institution”. This question received a Likert scale score of 3.6 with a standard deviation of 1.1 (Appendix L). It should be emphasized that while this score is lower than all others, it is still a positive score on the Likert scale (between “Agree” and “Neutral”). In addition, this question received the largest standard deviation, indicating that students are divided on this question. Nevertheless, the Center management and leadership take this result very seriously, and we will continue 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, which enables students and postdocs to spend 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	P9	**P10**
Inclusiveness	3.8	4.1	4.1	4.6	4.4	4.3	4.5	4.5	**4.8**
Teamwork	3.7	3.6	4.0	4.6	4.2	4.2	4.3	4.3	**4.5**
Open and timely communications	4.0	4.2	4.2	4.7	4.2	4.4	4.5	4.4	**4.7**
Agility/Decision Making	4.0	4.1	4.2	4.5	4.4	4.4	4.4	4.3	**4.7**
Focus on Performance	3.8	4.1	4.1	4.5	4.2	4.2	4.2	4.2	**4.6**

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. In fact, overall survey scores in period 10 have been the highest since the inception of the Center.

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

1d. Problems Encountered

While the departure of Associate Director of Education, **Lea Marlor**, only two months before the start of the summer education programs caused a challenging situation, the new Associate Director for Education, **Nicole McIntyre**, came with lots of experience from co-managing an REU program in the UC Berkeley EECS Department, and needed only very little time to manage the E^{3}S TTE and RET programs independently this summer.

E^{3}S senior investigator **Sakhrat Khizroev** moved from FIU to University of Miami in this period. Given that the Center is currently already in its sunsetting period, it was decided to keep the E^{3}S research project and all E^{3}S supported students at FIU. While the project will continue to be guided by **Sakhrat Khizroev**, **Osama Mohammed** (a distinguished professor and associate dean for research in the College of Engineering and Computing at FIU) will formally oversee the day-by-day E^{3}S research activities at FIU. There has not been a change in research direction at FIU.

2. Management and Communications Systems

Management: The governing body of the Center for E^{3}S is the Executive Committee, as described above. This committee continued to hold regularly scheduled meetings throughout the funding period to discuss the direction of the Center and make important decisions. All meetings are held by WebEx to allow remote participation of members from different institutions. This period, so far, the Executive Committee has met three times with the fourth and final meeting being scheduled for January 6, 2020 (see details below).

In addition to overseeing all Center activities and plans, a main focus of the Executive Committee has been the establishment of a lasting Center legacy in both education and research.

During last year's center-wide retreat (September 20-21, 2018) the E^{3}S leadership team has started preparations to minimize the impact of the scheduled budget reduction (overall 33 percent reduction) in the last 18 months of the Center (March 2019 through September 2020). Executive director, **Michael Bartl**, developed a plan/budget to minimize the administrative impact and to ensure the Center stays fully operational. In addition, the Executive Committee decided to consider research budget cuts in its annual review of proposed Center-internal research programs for funding period 10. While all funding decisions for period 10 programs were made based on the quality, impact and potential for Center legacy of proposed projects, the committee was sensitive to potential impact on graduate students and postdocs. Final discussions were made at the November 2 Executive Committee meeting. The review and voting process ended with unanimous agreement on all the proposed programs. In general, with the exception of **Connie Chang-Hasnain**, who decided to leave the Center due to other administrative commitments, all E^3S senior investigators were funded for periods 10 and 11 (through September 2019), as reported in the Research section of this Annual Report.

Table 7.3. Executive Committee Meetings – Period 10

Meeting Dates	Agenda Topics
April 30, 2019	Review of Period 9 Spending; Vote on Period 10 Budget; External Advisory Board Membership Review; Hiring Progress of New Education Director
July 11, 2019	Review and Ratification of By-Laws; Approval of Executive Board; Approval of External Advisory Board Membership; Annual Retreat Planning
September 20, 2019	Annual Retreat Debrief; Review of Budget and Planning for Further Reductions for Period 11; Center Legacy Updates, Plans and Execution
January 6, 2020	Review of the Center's Results vs. the Strategic Plan; Center Legacy Progress

Communications and Planning: The Annual Center-wide Retreat has traditionally been the foremost gathering and planning event for all Center faculty, students, postdocs and staff. Since the Center will sunset in September 2010, this year's event, held on the UC Berkeley campus on September 19 and 20, was the last regular retreat. As part of the retreat activities, all research, education and diversity programs as well as Center management and knowledge transfer activities were reviewed with respect to progress towards the main Center goals and legacy building. The retreat included research presentations from faculty, students and postdocs, representing all E^3S themes and system integration. These presentations are held on the first day of the retreat (see also retreat agenda, given as Appendix F). The first retreat day was also attended by representatives from four of our five industry partners: **Toshihiko Miyashita** (Applied Materials), **Paul Solomon** (IBM), **Uygar Avci** (Intel), and **Hwan Sung Choe** (Lam Research). **Stanley Williams** (HPE, ret.) was unable to attend. The second day featured presentations about education and diversity achievements and plans, reports by the executive director on Center management and center-wide output, and a diversity training/workshop on "Diversity, Equity and Inclusion in the Political Sphere" by E^3S diversity director, **Kedrick Perry**. The final part of the retreat was dedicated to the E^3S education legacy, with main focus on the progress of the E^3S e-book.

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.

The main communication tool of the Center has continued to be the E^3S website: https://e3s-center.berkeley.edu/, keeping 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^3S 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 have represented academia, national labs, and industry. All members and the chair of the External Advisory Board are appointed by the E^3S Executive Committee for limited terms:

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

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

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

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

Due to budget restrictions in the Center's sunsetting period, the E^3S Executive Committee decided, in consultation with the chair of the External Advisory Board, not to hold an annual meeting of the E^3S External Advisory Board. Instead, it was agreed that a written report to be submitted to the External Advisory Board in December 2019, detailing the Center's progress in research, education, diversity, knowledge transfer, and center management. The External Advisory Board will then review the written report and will provide written feedback to the Executive Committee.

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

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

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

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

- Toshihiko Miyashita, Applied Materials
- Paul Solomon, IBM
- Uygar Avci, Intel
- Hwan Sung Choe, Lam Research

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

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*

Journal Articles Published *(chronological)*

1. Y. Guo, P.-C. Shen, C. Su, A.-Y. Lu, M. Hempel, Y. Han, Q. Ji, Y. Lin, E. Shi, E. McVay, L. Dou, D. Muller, T. Palacios, J. Li, X. Ling, and **J. Kong**, "Additive manufacturing of patterned 2D semiconductor through recyclable masked growth," *Proceedings of the National Academy of Sciences*, vol. 116, no. 9, pp. 3437-3442, Feb 2019.
2. W. S. Leong, H. Wang, J. Yeo, F. Martin-Martinez, A. Zubair, P.-C. Shen, Y. Mao, T. Palacios, M. Buehler, J.-Y. Hong, and **J. Kong**, "Paraffin-enabled graphene transfer," *Nature* communications, vol. 10, no. 1, Feb 2019.
3. J. Lin, X. Zhao, I. Manglano, D. A. Antoniadis, and **J. A. del Alamo**, "A Scaling Study of Excess OFF-State Current in InGaAs Quantum-Well MOSFETs," *IEEE Transactions on Electron Devices*, vol. 66, no. 3, pp. 1208-1212, Mar 2019.
4. A. Vidaña, **D. Zubia**, M. Martinez, E. Acosta, J. Mireles Jr., **T.-J. K. Liu**, and S. Almeida, "Conductivity modulation in strained transition-metal-dichalcogenides via micro-electro-mechanical actuation," *Semiconductor Science and Technology*, vol. 34, no. 4, p. 45013, Mar 2019.
5. J. Hong, T. Yang, A. N'Diaye, **J. Bokor**, and L. You, "Effects of Interface Induced Natural Strains on Magnetic Properties of FeRh," *Nanomaterials*, vol. 9, no. 4, p. 574, Apr 2019.
6. S. K. Vadlamani, S. Agarwal, D. T. Limmer, **S. G. Louie**, **F. R. Fischer**, and **E. Yablonovitch**, "Tunnel-FET Switching Is Governed by Non-Lorentzian Spectral Line Shape," *Proceedings of the IEEE*, pp. 1-10, Apr 2019.
7. X. Zhao, A. Vardi and **J. A. del Alamo**, "Excess OFF-State Current in InGaAs FinFETs: Physics of the Parasitic Bipolar Effect," *IEEE Transactions on Electron Devices*, vol. 66, no. 5, pp. 2113-2118, May 2019.
8. D. H. Lien, S. Z. Uddin, M. Yeh, M. Amani, H. Kim, J. W. Ager, **E. Yablonovitch**, and **A. Javey**, "Electrical suppression of all nonradiative recombination pathways in monolayer semiconductors," *Science*, vol. 364, no. 6439, pp. 468-471, May 2019.
9. J. Hong, Q. Luo, S. Jung, S. Je, Y. Kim, M. Im, C. Hwang, **S. Khizroev**, S. Chung, and L. You, "Shape transformation and self-alignment of Fe based nanoparticles," *Nanoscale Advances,* vol. 1, no. 7, pp. 2523-2528, May 2019.
10. S. Fathipour, S. F. Almeida, Z. A. Ye, B. Saha, **F. Niroui**, **T.-J. K. Liu** and **J. Wu**, "Reducing adhesion energy of nano-electro-mechanical relay contacts by self-assembled Perfluoro (2,3-Dimethylbutan-2-ol) coating," *AIP Advances*, vol. 9, no. 5, p. 55329, May 2019.
11. N. Roschewsky, E. Walker, P. Gowtham, S. Muschinske, F. Hellman, S. Bank, and **S. Salahuddin**, "Spin-orbit torque and Nernst effect in Bi-Sb/Co heterostructures," *Physical Review B*, vol. 99, no. 19, pp. 195103-195108, May 2019.
12. J. Hong, X. Li, O. Lee, W. Tian, **S. Khizroev**, **J. Bokor**, and L. You, "Demonstration of spin transfer torque (STT) magnetic recording," *Applied Physics Letters*, vol. 144, no. 24, p. 243101, Jun 2019.
13. A. El-Ghazaly, B. Tran, A. Ceballos, C.-H. Lambert, A. Pattabi, **S. Salahuddin**, F. Hellman, and **J. Bokor**, "Ultrafast magnetization switching in nanoscale magnetic dots," *Applied Physics Letters*, vol. 144, no. 23, p. 232407, Jun 2019.
14. X. Zhao, A. Vardi, and **J. A. del Alamo**, "Fin-Width Scaling of Highly-Doped InGaAs Fins," *IEEE Transactions on Electron Devices*, vol. 66, no. 6, pp. 2563-2568, Jun 2019.
15. S. von Kugelgen, I. Piskun, J. H. Griffin, C. T. Eckdahl, N. N. Jarenwattananon, **F. R. Fischer**, "Templated Synthesis of End-Functionalized Graphene Nanoribbons Through Living Ring-

Opening Alkyne Metathesis Polymerization," *J. Am. Chem. Soc.*, vol. 141, no. 28, pp. 11050-11058, Jun 2019.

16. A. Vidaña, E. Acosta, M. Martinez, S. Almeida, J. Mireles, and **D. Zubia**, "Exponential conductivity increase in strained MoS2 via MEMS actuation," *MRS Advances*, vol. 4, no. 38-39, pp. 2135-2142, Jun 2019.
17. Y. Lin, Q. Ma, P.-C. Shen, Y. Bie, A. Liao, B. Han, N. Mao, X. Zhang, X. Ji, Y. Zhang, J. Yin, S. Huang, M. Dresselhaus, P. Jarillo-Herrero, X. Ling, **J. Kong** and T. Palacios, "Asymmetric Hot-Carrier Thermalization and Broadband Photoresponse in Graphene-2D Semiconductor Lateral Heterojunctions," *Science Advances*, vol. 5, no. 6, pp. eaav1493, Jun 2019.
18. N. M. Andrade, S. Hooten, S. A. Fortuna, K. Han, **E. Yablonovitch**, and **M. C. Wu**, "Inverse design optimization for efficient coupling of an electrically injected optical antenna-LED to a single-mode waveguide," *Optics Express*, vol. 27, no. 14, pp. 19802-19814, Jul 2019.
19. K. Han, G. H. Ahn, J. Cho, D.-H. Lien, M. Amani, S. B. Desai, G. Zhang, H. Kim, N. Gupta, **A. Javey**, and **M. C. Wu**, "Bright electroluminescence in ambient conditions from WSe2 p-n diodes using pulsed injection," *Applied Physics Letters*, vol. 115, no. 1, p. 11103, Jul 2019.
20. B. Navarrete, M. Stone, K. Luongo, A. Hadjikhani, P. Wang, J. Hong, P. Liang, **J. Bokor**, and **S. Khizroev**, "Nanomagnetic particle-based information processing," *IEEE Transactions on Nanotechnology*, vol. 18, pp. 983-988, Sep 2019.
21. P. Zhao, R. Wang, D.H. Lien, Y. Zhao, H. Kim, J. Cho, G.H. Ahn, and **A. Javey**, "Scanning Probe Lithography Patterning of Monolayer Semiconductors and Application in Quantifying Edge Recombination," *Advanced Materials*, Early View, 1900136, Sep 2019.
22. E. A. Tremsina, N. Roschewsky, and **S. Salahuddin**, "Micromagnetic analysis and optimization of spin-orbit torque switching processes in synthetic antiferromagnets," *Journal of Applied Physics*, vol. 126, no. 16, p. 163905, Oct 2019.
23. P.-C. Shen, C. Lin, K. H. Teo, and **J. Kong**, "Ferroelectric Memory Field-effect Transistors using CVD Monolayer MoS2 as Resistive Switching Channel," *Applied Physics Letters*, vol. 116, pp. 033501, Jan 2020.
24. D. Toledo, B. Navarrete, M. Stone, K. Luongo, P. Wang, P. Liang, and **S. Khizroev**, "A theoretical study of switching energy efficiency in sub-10-nm spintronic devices," *J. Magnetism and Magnetic Materials*, vol. 494, 165776, Jan 2020.
25. S. Bae and **J. Kim**, "Graphene allows spontaneous relaxation towards dislocation-free heteroepitaxy," *Nature Nanotechnology*, (Accepted)

Under Review/Submitted *(chronological)*

1. G. Veber, C. S. Diercks, C. Rogers, W. S. Perkins, J. Ciston, A. Liebman-Palaez, C. Zhu, **F. R. Fischer**, "Reticular Growth of Graphene Nanoribbon 2D Covalent Organic Frameworks," *ChemRxiv*, 2019. (Submitted)
2. J. Hong, H.-N. Hwang, A. T. N'Diaye, J. Liang, G. Chen, Y. Park, L. T. Singh, Y. G. Jung, J.-H. Yang, J.-I. Jeong, A. K. Schmid, E. Arenholz, H. Yang, **J. Bokor**, C.-C. Hwang and L. You, "The interfacial spin modulation of graphene on Fe(111)," *Proc. Nat. Acad. Sci.*, 2019. (Submitted)
3. D. J. Rizzo, G. Veber, J. Jiang, R. McCurdy, T. Cao, C. Bronner, T. Chen, **S. G. Louie**, **F. R. Fischer**, M. F. Crommie, "Inducing Metallicity in Graphene Nanoribbons via Zero-Mode Superlattices," *arXiv*, 2019. (Submitted)
4. R. Naous, L. Supic, Y. Kang, R. Seradejovic, A. Singhani, **V. Stojanovic**, "Tuning Algorithms and Generators for Efficient Edge Inference," *arXiv*, 2019. (Submitted)
5. P. Li, C. Bi, J. Wisser, L. Riddiford, X. Sun, A. Vailionis, M. Veit, A. Altman, X. Li, M. DC, **S. Wang**, Y. Suzuki, and S. Emori, "Charge-to-Spin Conversion Mechanisms in Epitaxial Pt Probed by Spin-Orbit Torques in a Magnetic Insulator," *Physical Review Letters*, 2019. (Submitted)

Conference Proceedings *(chronological)*

1. S. Hooten, N. M. Andrade, S. A. Fortuna, K. Han, **M. C. Wu**, and **E. Yablonovitch**, "nanoLED Wavelength Division Multiplexer Analysis," *CLEO*, May 2019.
2. R. Naous and **V. Stojanovic**, "Edge inference with NEM relays," *2019 IEEE SOI–3DI–Subthreshold (S3S) Microelectronics Technology Unified Conference*, San Jose, California, October 14-17, 2019.
3. X. Li and **S. Wang**, "Materials Requirements of High-Speed and Low-Power Spin-Orbit-Torque Magnetic Random-Access Memory," *2019 IEEE SOI–3DI–Subthreshold (S3S) Microelectronics Technology Unified Conference*, San Jose, California, October 14-17, 2019.
4. X. Li and **S. Wang**, "Materials Requirements of High-Speed and Low-Power Spin-Orbit-Torque Magnetic Random-Access Memory," *Annual Conference on Magnetism and Magnetic Materials*, Las Vegas, Nevada, November 4-8, 2019.

1aii. Books and Book Chapters

1. C. Bi, N. Sato, and **S. X. Wang**, "Spin-orbit torque magnetoresistive random-access memory (SOT-MRAM)," in *Advances in Non-volatile Memory and Storage Technology*, Editors: Y. Nishi and B. Magyari-Köpe, Elsevier, 2019.
2. The nanomechanics chapter of E^3S e-book has been finished in this period and will be published on nanoHUB.org shortly.

1b. Conference Presentations

Talks: *(excluded are period 10 talks that have published proceedings)*

1. J. A. del Alamo, "Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs," *International Workshop on Materials Science & Device Physics for Advanced Electron Devices*, University of Tokyo, Tokyo, Japan, Mar 2019.
2. S. G. Louie, "Topological Effects in 1D and 2D Materials: Topological Band Engineering, Optical Selection Rules, and Excitonic Shift Currents," *Annual APS March Meeting*, Boston, MA, Mar 2019.
3. T. Cao, "Theory of Topological Phases and Topological Band Engineering of Graphene Nanoribbons," *2019 American Physical Society (APS) March Meeting*, Boston, Massachusetts, Mar 2019.
4. F. Zhao, "Effects of Electric Field on Topological Phases in Graphene Nanoribbons," *2019 American Physical Society (APS) March Meeting*, Boston, Massachusetts, Mar 2019.
5. S. G. Louie, "Topological Effects in 1D and 2D Materials: Topological Band Engineering, Optical Selection Rules, and Excitonic Shift Currents," *Materials Research Society Spring Meeting*, Phoenix, AZ, Apr 2019.
6. J. Bokor,"Ultrafast Spintronics: A Novel Approach for MRAM Speedup," *IEEE International Nanodevices and Computing Conference,* Grenoble, France, Apr 2019.
7. S. X. Wang, "Interfacial engineering of SOT-MRAM," *4th International Workshop on Spintronics Memory and Logic (SML)*, Beijing, May 2019.
8. J. Kong, "Synthesis and Integration of Two Dimensional Materials," *TechConnect, World Conference & Expo*, Jun 2019.

9. F. Fischer, “Forging Symmetry Protected Topological States into Metallic Graphene Nanoribbons,” *International Conference on Novel Aromatics (ISNA)*, Sapporo, JP, Jul 2019.
10. J. Bokor, “Picosecond Magnetic Switching by Pure Charge Current Pulses,” *Gordon Research Conference on Spin Dynamics in Nanostructures*, Les Diablerets, Switzerland, Jul 2019.
11. E. Acosta, A. Vidana, R. Zubia, S. Almeida, J. Mireles, D. Zubia, “MEMS Device for Electrical/Optical Characterization of Functional 2D Materials at High Strain,” *XXVIII International Materials Research Congress*, Cancun, Mexico, Aug 2019.
12. R. Zubia, A. Ye, T.-J. King Liu, “Microelectromechanical Relay Circuits for Digital Computing at Low Operating Voltage,” *XXVIII International Materials Research Congress*, Cancun, Mexico, Aug 2019.
13. S. G. Louie, “Interaction and Topological Effects in Atomically Thin One- and Two-dimensional Materials,” *9th Symposium on Two-dimensional Materials*, Copenhagen, Aug 2019.
14. J. Bokor, “The End of Moore’s Law,” *Co-Design Conference*, Stanford University, Sep 2019.
15. J. Bokor, “Landauer Switching Limit,” *Co-Design Conference*, Stanford University, Sep 2019.
16. X. Li, “Materials Requirements of High-Speed and Low-Power Spin-Orbit-Torque Magnetic Random-Access Memory”, *2019 IEEE SOI–3DI–Subthreshold (S3S) Microelectronics Technology Unified Conference*, San Jose, CA, Oct 2019.
17. S. G. Louie, “Exploring New Territories of the 2D Materials World: Topological Phases, Multi-Particle Excitations, and Excitons in Optical Field Driven ARPES,” *The 9th International Workshop on Quantum Energy*, Xiamen, China, Oct 2019.
18. S. G. Louie, “Interaction and Topological Effects in Atomically Thin One- and Two-dimensional Materials,” *International Conference on Frontier Sciences*, Beijing, China, Nov 2019.
19. X. Li, "Materials Requirements of High-Speed and Low-Power Spin-Orbit-Torque Magnetic Random-Access Memory", *Annual Conference on Magnetism and Magnetic Materials*, Las Vegas, NV, Nov 2019.

Posters

1. N. M. Andrade, S. A. Fortuna, and M. C. Wu, “Efficient Waveguide-Coupling of Electrically Injected Optical Antenna-LED,” *Berkeley Sensor & Actuator Center*, Mar 2019.
2. E. Acosta, M. Martinez, A. Vidana, S. Almeida, J. Mireles, D. Zubia, “MEMS Process and Characterization for Strain-Engineered 2D Materials,” *Materials Research Society Spring Meeting*, Phoenix, AZ, Apr 2019.
3. A. Vidana, E. Acosta, M. Martinez, S. Almeida, J. Mireles, D. Zubia, “Large conductivity increase in strained MoS2 via MEMS actuation,” *Materials Research Society Spring Meeting*, Phoenix, AZ, Apr 2019.
4. F. Fischer, “Engineering Topological States in Graphene Nanoribbons,” *Physical Organic Chemistry Gordon Research Conference*, Holderness, Jun 2019.
5. N. M. Andrade, S. A. Fortuna, and M. C. Wu, “Efficient Waveguide-Coupling of Electrically Injected Optical Antenna Based nanoLED,” *Berkeley Sensor & Actuator Center*, Sep 2019.

1c. Other Dissemination Activities (in chronological order)

1. J. A. del Alamo, “Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs,” Ecole Federale Polytechnique de Lausanne, Lausanne, Switzerland, Feb 2019.

2. J. A. del Alamo, "Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs," IMEC, Leuven, Belgium, Feb 2019.
3. J. A. del Alamo, "Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs," NTT, Atsugi, Kanagawa, Japan, Mar 2019.
4. J. Bokor, "Ultrafast Spintronics: A Novel Approach for MRAM Speedup," Jean-Yves Bigot Memorial Symposium, Strasbourg, France, Apr 2019.
5. J. A. del Alamo, "Nanoscale III-V Electronics: InGaAs FinFETs and Vertical Nanowire MOSFETs," HRL Laboratories, Malibu, CA, Apr 2019.
6. E. Yablonovitch, Erwin Schrödinger Distinguished Lecture, Austrian Academy of Sciences, Vienna, May 2019.
7. F. Fischer, "There's plenty of room at the bottom…just no room for error," University of Erlangen, Chemistry Seminar, Jun 2019.
8. S. G. Louie, "Interaction and Topological Effects in Atomically Thin One- and Two-dimensional Materials," Institute of Physics Workshop, Taipei, Taiwan, Jun 2019.
9. F. Fischer, "Forging Symmetry Protected Topological States into Metallic Graphene Nanoribbons," Swiss Federal Institute of Technology, Switzerland, Jun 2019.
10. F. Fischer, "Forging Symmetry Protected Topological States into Metallic Graphene Nanoribbons," University of Cambridge, UK, Sep 2019.
11. F. Fischer, "There's plenty of room at the bottom…just no room for error," University of Oxford, UK, Sep 2019.
12. F. Fischer, "There's plenty of room at the bottom…just no room for error," Georgetown University, Oct 2019.
13. F. Fischer, "There's plenty of room at the bottom…just no room for error," CU Boulder, Oct 2019.
14. F. Fischer, "There's plenty of room at the bottom…just no room for error," Texas A&M, Nov 2019.

2. *Awards & Honors*

Recipient	Reason for Award	Award Name	Sponsor	Date	Award Type
Tsu-Jae King Liu	Contributions to research and industry	Silicon Valley Engineering Hall of Fame	Silicon Valley Engineering Council	Feb 2019	Scientific, Industry
Eli Yablonovitch	Overall distinction in optics	2019 Frederic Ives Medal/Jarus W. Quinn Prize	Award of the Optical Society	Feb 2019	Scientific
Sayeef Salahuddin		Fellow, IEEE	IEEE	Feb 2019	Scientific
Eli Yablonovitch		Benjamin Franklin Medal in Electrical Engineering	Franklin Institute	April 2019	Scientific
Steven G. Louie	Research achievements	Fellow of the Materials Research Society	Materials Research Society	Apr 2019	Scientific

Matthew Rollings		NSF Graduate Fellowship	NSF	Apr 2019	Scientific, Fellowship
Sayeef Salahuddin		IEEE EDS George E Smith Award	IEEE	Jul 2019	Scientific
Zhixin Alice Ye		DE Shaw Exploration Fellowship	DE Shaw	Aug 2019	Fellowship
Tsu-Jae King Liu	Contributions to nanometer-scale field-effect transistor and MEM relay technology	Asian American Engineer of the Year Distinguished Science & Technology Award	Chinese Institute of Engineers/USA	Aug 2019	Scientific, Industry
Sayeef Salahuddin		Fellow, APS	APS	Oct 2019	Scientific
Sri Krishna Vadlamani	Outstanding research	Best Student Paper Award	IEEE S3S Conference	Oct 2019	Scientific
Safi Mohammed	Outstanding research	Best Poster (Engineering)	SACNAS	Nov 2019	Scientific
Ming C. Wu		Robert Bosch Micro and Nano Electro Mechanical Systems Award	IEEE Electron Device Society	Nov 2019	Scientific
Zhixin Alice Ye	Outstanding research	Kavli Research Exchange Programme Award	Winton Kavli Programme for Physics of Sustainability	Jan 2020	Scientific, Fellowship

3. *Graduates*

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Kamaria Kermah	Bachelor	Feb 2019	4	Industry
Kimberley Fountain	Bachelor	May 2019	4	Industry

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree*	Placement
Niklas Roschewsky	PhD, Physics	May 2019		Lam Research
Kevin Han	PhD, EECS	May 2019	5	UC Berkeley (Postdoc)
Patrick Xiao	PhD, EECS	May 2019	6	Sandia National Laboratories (Postdoc)
Kevin Luongo	PhD, ECE	Jun 2019		University of Miami
Aldo Vidana	M.S., EE	Aug 2019		Army Research Lab
Gregory Veber	PhD, Chemistry	Dec 2019	5	

Postdocs

Name	Departure Date	Placement
Sara Fathipour	Feb 2019	Intel
Sergio Almeida	Apr 2019	DiDi Labs
Wenjie Lu	Jun 2019	Analog Devices Inc.
Amal El-Ghazaly	Aug 2019	Cornell University
Seth Fortuna	Sep 2019	Sandia National Lab
Rawan Naous	Oct 2019	TSMC

4. General Outputs of Knowledge Transfer Activities

Patents:

Patent Name	Inventors/Authors	Number	Application Date	Receipt Date
Writing of a Magnetic Memory with Electric Pulses	Y. Yang, J. Gorchon, R.B. Wilson, C.H.A. Lambert, S. Salahuddin, J. Bokor	US Patent 10,388,349	Sept 21, 2017	March 21, 2019
Tunable Light Emitting Devices and Applications Thereof	V. Bulovic, W. Chang, J.H. Lang, A. Murarka, A.I. Wang	US Patent 10,256,596		April 9, 2019
Nanoparticle Based Computing Architecture	S. Khizroev, R. Guduru	US Patent 10,381,466	Oct 12, 2018	Aug 13, 2019
Tunneling Nanomechanical Switches and Tunable Plasmonic Nanogaps	V. Bulovic, J.H. Lang, F. Niroui, E. Sletten, T.M. Swager	US Patent 10,475,601		Nov 12, 2019
Ohmic Contacts to Low-Dimensional Materials Using Bismuth	P. Shen, J. Kong	Invention Disclosure MIT TLO	July 12, 2019	
Low Bandgap Graphene Nanoribbon Electronic Devices	F. Fischer, J. Bokor, R. Mc Curdy, J.P. Llinas, D. Joshi, Z. Mutlu, G. Weber	Invention Disclosure BK-2019-145-1		

Other Outputs of Knowledge Transfer Activities:

- **Felix Fischer** (*Berkeley*) has formed a partnership with Roswell Biotechnologies for use of graphene nanoribbons in biotechnology applications.
- **Jesus del Alamo** (*MIT*) started a research partnership with Intel on exploring the limits of vertical-nanowire TFETs in the nanoscale.

- **Jesus del Alamo** (*MIT*) has a continued partnership with Lam Research about his 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.
- **Jing Kong** (*MIT*) had multiple visits and research discussions about joint projects with TSMC.
- Former E^3S investigator **Philip Wong** (Stanford) is now a vice president at TSMC.
- **Michael Bartl** (*Berkeley*) participated in the 2019 Lam Tech Symposium.
- **Junqiao Wu** formed a start-up company, DeepRed Technologies, which focuses on infrared imaging sensitivity enhancement.
- Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) collaborates with Texas Instruments and Atomera on projects about SegFET transistor technology for RF applications.
- Deputy director **Jeffrey Bokor** and Theme I investigator **Felix Fischer** (both *Berkeley*) have a joined research project with TSMC on the development of graphene nanoribbon transistors.

5a. *Participants*

In the current reporting period, the Center has 93 participants. Funding of faculty, postdoctoral, graduate student, and undergraduate student participants is summarized as follows.

Period 10	**Summer**	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	7	1	0	12	**20**

	Funded by E^3S			**Other Funding Source**	**Total Participants**
Category	50% or more	Less than 50%	**Total**		
Postdocs	5	3	**8**	3	**11**
Grad Students	19	6	**25**	10	**35**
Undergrads	3	11	**14**	0	**14**
TOTAL					**60**

PARTICIPANTS - PERIOD 10

	Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Veteran		Citizenship
20	Faculty	10	Berkeley	17	E.E.	17	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	12	US Citizens
		7	MIT	1	Mats Sci	3	F	0	Visual Impairment	17	Not Hispanic or Latino	7	Asian	20	No	6	Permanent Resident
		1	Stanford	2	Chemistry			0	Mobility/Orthopedic Impairment	2	Decline to State	0	Black or African American	0	Decline to State	1	Other non-US Citizen
		1	UTEP	1	Physics			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			1	Decline to State
		0	LATTC	1	MechE			17	None			11	White			0	Not Available
		1	FIU					3	Decline to State			2	Decline to State				
		0	Other					0	Not Available			0	Not Available				
11	Postdocs	5	Berkeley	9	E.E.	7	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	2	US Citizens
		4	MIT	1	Mats Sci	4	F	0	Visual Impairment	10	Not Hispanic or Latino	6	Asian	11	No	0	Permanent Resident
		2	Stanford	1	MechE			0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	0	Decline to State	9	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	FIU					11	None			4	White			0	Not Available
								0	Decline to State			0	Decline to State				
								0	Not Available			0	Not Available				
35	Graduate Students	22	Berkeley	24	E.E.	29	M	0	Hearing Impairment	4	Hispanic or Lantino	1	American Indian or Alaskan Native	0	Yes	12	US Citizens
		7	MIT	2	Mats Sci	6	F	0	Visual Impairment	28	Not Hispanic or Latino	17	Asian	32	No	3	Permanent Resident
		0	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	3	Decline to State	3	Black or African American	3	Decline to State	17	Other non-US Citizen
		2	UTEP	0	MechE			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			3	Decline to State
		4	FIU	7	Chemistry			31	None			11	White			0	Not Available
				0	Other			4	Decline to State			4	Decline to State				
								0	Not Available			0	Not Available				
14	Undergraduate Students	1	Berkeley	8	E.E.	10	M	0	Hearing Impairment	5	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	20	US Citizens
		0	MIT	1	Mats Sci	3	F	0	Visual Impairment	7	Not Hispanic or Latino	5	Asian	13	No	4	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	1	Black or African American	0	Decline to State	1	Other non-US Citizen
		3	UTEP	0	MechE			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	LATTC	1	Chemistry			13	None			6	White			0	Not Available
		0	CCC	2	Other			0	Decline to State			4	Decline to State				
		0	FIU					0	Not Available			0	Not Available				
		10	Other														
4	Visiting Scholars	0	Berkeley	1	Engineering	3	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	4	US Citizens
		0	MIT	1	Chemistry	1	F	0	Visual Impairment	3	Not Hispanic or Latino	0	Asian	4	No	0	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	0	Decline to State	0	Other non-US Citizen
		0	UTEP	1	Mathematics			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	FIU	3	Other			4	None			3	White			0	Not Available
		4	Other					0	Decline to State			0	Decline to State				
								0	Not Available			0	Not Available				
9	Staff	9	Berkeley	0	E.E.	**4**	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	9	US Citizens
		0	MIT	0	Mats Sci	**5**	F	0	Visual Impairment	8	Not Hispanic or Latino	2	Asian	9	No	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	2	Black or African American	0	Decline to State	0	Other non-US Citizen
		0	UTEP	9	E3S			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	FIU	0	Other			6	None			4	White			0	Not Available
								3	Decline to State			1	Decline to State				
								0	Not Available			0	Not Available				
93	**TOTAL PARTICIPANTS**																

Center for Energy Efficient Electronics Science

5b. Affiliates

AFFILIATES - PERIOD 10

	Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship
0	Faculty	0	Berkeley	0	E.E.	0	M	0	Hearing Impairment	0	Hispanic or Lantino	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	0	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			0	None			0	White	0	Not Available
		0	CCC	0	Other			0	Decline to State			0	Decline to State		
		0	Other					0	Not Available			0	Not Available		
4	Postdocs	4	Berkeley	4	E.E.	4	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	3	Not Hispanic or Latino	1	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	0	Black or African American	4	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	FIU	0	ME			4	None			2	White	0	Not Available
				0	Other			0	Decline to State			1	Decline to State		
								0	Not Available			0	Not Available		
7	Graduate Students	6	Berkeley	6	E.E.	6	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	4	US Citizens
		0	MIT	1	Mats Sci	1	F	0	Visual Impairment	5	Not Hispanic or Latino	4	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			1	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	FIU	0	ME			6	None			2	White	0	Not Available
				0	Other			0	Decline to State			1	Decline to State		
								0	Not Available			0	Not Available		
0	Undergraduate Students	0	Berkeley	0	E.E.	0	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	0	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	0	ChemE			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			0	None			0	White	0	Not Available
		0	CCC	0	Other			0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
0	Staff	0	Berkeley	0	E3S	0	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	OEOP	0	F	0	Visual Impairment	0	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	TAP			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC					0	None			0	White	0	Not Available
								0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
11	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	Knowledge Transfer, Research, and BETR Center	Yes
2.	Applied Materials	Company	Santa Clara, CA	Chong-Ping Chang	Knowledge Transfer (BETR Center)	No
3.	TSMC	Company	Taiwan San Jose, CA	Carlos Diaz	Research Collaboration (BETR Center)	Yes
4.	Texas Instruments	Company	Dallas, TX	Jim Wieser	Research Collaboration (BETR Center)	Yes
5.	Atomera	Company	Los Gatos, CA	Robert Mears	Research Collaboration (BETR Center)	Yes
6.	Universidad Autonoma de Ciudad Juarez, Mexico	University	Juarez, Mexico	Professor Mireles	Research Collaboration	Yes
7.	Intel	Company	Hillsboro, OR, CA	Uygar Avci	Research Collaboration, Knowledge Transfer	No
8.	IBM	Company	Yorktown Heights, NY	Paul Soloman	Knowledge Transfer	No
9.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Eboney Hearn	Education & Diversity	No
10.	MIT Office of the Dean of Graduate Education	University	Cambridge, MA	Gloria Anglon	Education & Diversity	No
11.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Merryl Owen	Education & Diversity	No

12.	UC Berkeley Summer Sessions	University	Berkeley, CA	Richard Russo	Education	No
13.	Berkeley Engineering Graduate Outreach	University	Berkeley, CA	Meltem Erol	Education & Diversity	No
14.	Berkeley Office of Graduate Diversity	University	Berkeley, CA	Cynthia Ladd-Viti	Education & Diversity	No
15.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon, Meltem Erol	Education & Diversity	No
16.	UC Berkeley Black Graduate Engineering and Science Students	University	Berkeley, CA	Benjamin Osoba	Education & Diversity	No
17.	SUBERB REU Program	University	Berkeley, CA	Audrey Sillers	Education & Diversity	No
18.	TBSI Institute	University	Berkeley, CA	Alice Tsai	Education & Diversity	No
19.	Amgen Scholars Program	University	Berkeley, CA	Audrey Knowlton	Education & Diversity	No
20.	Joint Bioenergy Institute	University	Berkeley, CA	Irina Silver	Education & Diversity	No
21.	Skydeck	University	Berkeley, CA	Caroline Winnett	Knowledge Transfer, Education	No
22.	MESA Engine	University	UC Office of the President	Mindy Rieger	Education & Diversity	No
23.	Quantitative Biosciences, QB3	University	Berkeley, CA	Donna Hendricks	Education & Diversity	No
24.	California Community College System	University	Sacramento, CA	Pam Walker	Education & Diversity	No

7. *Summary Table for Internal NSF Reporting Purposes*

1.	The number of participating institutions (all academic institutions that participate in activities at the Center).	6
2.	The number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center).	6
3.	The total current year leveraged support (sum of funding for the Center from all sources other than NSF-STC) [Leveraged funding includes both cash and in-kind support related to Center activities, but not funds awarded to individual PIs.]	$1,003,247
4.	The number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF).	93

8. *Media Publicity of Center*

a. Hopper-Dean Foundation gift of $2M bolsters EECS diversity initiatives
http://newsletter.eecs.berkeley.edu/2019/11/hopper-dean-gift/?_ga=2.217986326.1292375735.1574084950-1391235388.1562355994
b. Engineering research entices community college students to pursue STEM careers
https://engineering.berkeley.edu/2019/08/engineering-research-entices-community-college-students-pursue-stem-careers

IX. INDIRECT/OTHER IMPACTS

International Activities:

- **Eli Yablonovitch** gave talks related to Energy Efficient Electronic Systems at various locations outside the U.S., including the Erwin Schrödinger Distinguished Lecture at the Austrian Academy of Sciences in Vienna, Austria.
- **Steven Louie** gave talks on low-dimensional nanosystems at various locations outside the U.S., including Taiwan, Denmark, and China.
- **Jesus del Alamo** gave talks on III-V MOSFETs and TFETs for CMOS in Switzerland, Belgium, and Japan.
- **Jeffrey Bokor** gave talks on ultrafast magnetic switching at various locations outside the U.S., including France and Switzerland.
- **Felix Fischer** gave talks on carbon nanoribbons at various locations outside the U.S., including Germany, United Kingdom, and Switzerland.

Education and Diversity:

- Community College Students: Impacted >44% 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^3S Transfer-to-Excellence REU program to community college students outside of disciplines affiliated with the Center from five to fifteen summer students annually. The Site was renewed in 2015 and was again renewed in 2018. During the summer 2019 (Period 10), the Center hosted 15 community college students from science and engineering majors in 11 different labs on Berkeley's campus. These students research focused on robotics and biotechnology. Over the Center's lifespan, E^3S has hosted 118 community college students from 51 institutions from every region in the state of California. Of the participants, 89% (105) have at least one identity underrepresented in science or engineering. Among the students eligible to transfer (excludes summer 2019 cohort), 94% (97) have transferred to a 4-year institution.

  The TTE REU research projects were advised by 46 faculty mentors and supervised by graduate student and postdoc mentors. Our program evaluation data shows that these mentors feel better prepared for future faculty careers as they gain skills in project management, supervision, teaching, and communication through the program.

- Community College Faculty: The E^3S Teacher Fellows Program and Research Experience for Teachers (RET) Site award (established in 2014) has continued in period 10. Five community college faculty members from engineering and chemistry departments at California community colleges spent eight weeks in the program, focused on curriculum development. Four of the five community college faculty members were past participants and had already done research through the program in the past. At the conclusion of the summer, all faulty members developed a course module or lab assignment, which will be taught at their respective community college during the 2019-2020 academic year.

- E^3S Executive Director, **Michael Bartl**, served as an invited panelist at the Northern California Forum for Diversity in Graduate Education on April 6, 2019. This event has been held for over 25 years as a joint activity between the University of California and California State University systems, as well as some of California's independent/private universities (Mills, USF, Stanford, Saint Mary's, UOP, and more). The goal is to bring together more than 1,000 minority undergraduates (and some master's students) for a day-long series of workshops and panels designed to inform them about various aspects of graduate study, including how to apply, how to acquire funding, how to prepare for the GRE, and succeed in a graduate program. Students are invited on the basis of academic standing and interest in graduate education. In addition, over 150 recruiters from institutions across the country are present at the recruiter fair.

- E^3S Diversity Director, **Kedrick Perry**, was a guest speaker in the UC Berkeley College of Engineering Dean's Communication course, which is open to all engineering students and teaches them how to communicate their STEM research projects. During his guest lecture on October 21, the topics of diversity and inclusion, including microaggressions and other types of less overt biased behavior, as well as types of diversity/privilege (ableism, straight privilege etc.) were discussed.

Additional other impacts include:

- An undergraduate engineering science major and an electrical engineering and computer science major have been workstudy office assistant during this reporting period. Their work in support of the Center's undergraduate programs has provided information and encouragement to them as they aspire to pursue careers in STEM fields

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

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XI. APPENDICES

Appendix A: Biographical Information of New Faculty and Staff Members

New Faculty in Period 10:

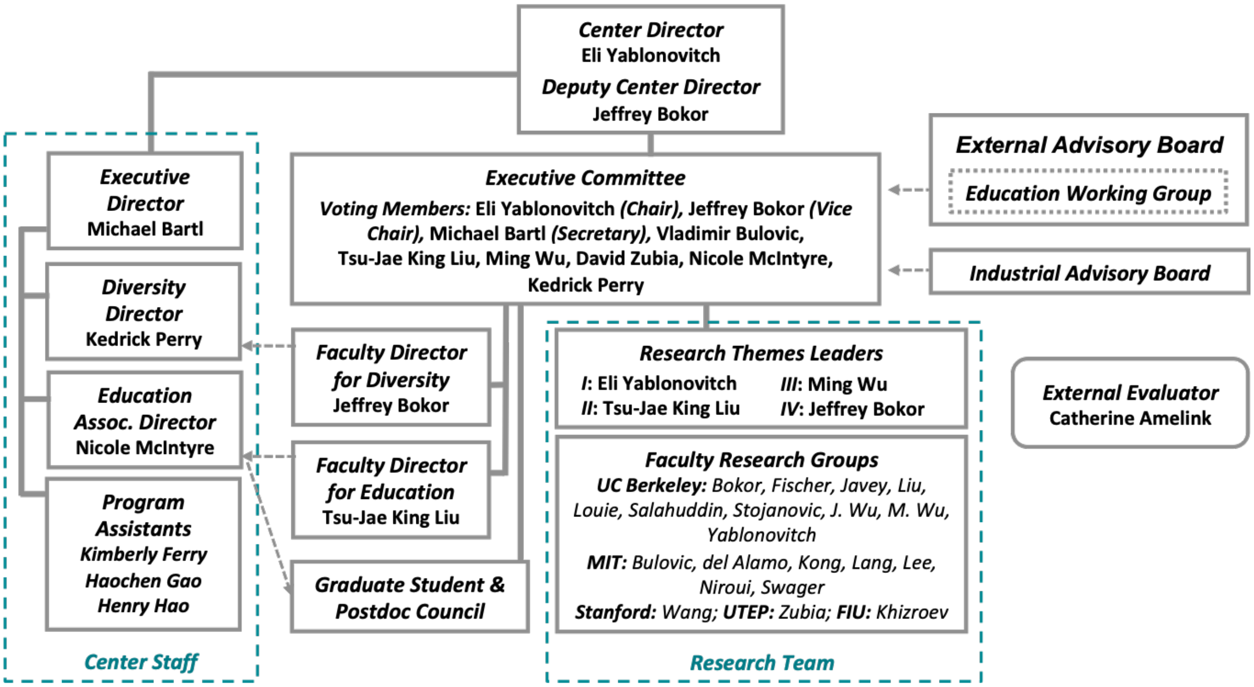
Osama Mohammed is a Distinguished Professor of Electrical and Computer Engineering and the Associate Dean of Research at the College of Engineering and Computing. He is the Director of the Energy Systems Research Laboratory at Florida International University. He received his M.S. and Ph.D. degrees in Electrical Engineering from Virginia Polytechnic Institute and State University. Professor Mohammed is internationally known for his many contributions in the energy field and related areas. He is an IEEE Fellow.

New Staff Member in Period 10:

Nicole McIntyre joined the Center for Energy Efficient Electronics Science (E^3S) as the Associate Director of Education in May 2019. Previously, she was the Lead Adviser and Program Coordinator for UC Berkeley's Department of Electrical Engineering and Computer Sciences. In this role, she worked with staff and faculty to administer the campus's two largest academic programs. Nicole holds degrees in Psychology and Social Welfare from the University of California, Berkeley, and a graduate degree in Educational Leadership from the University of San Francisco. She is committed to creating equitable and accessible public institutions of higher education, including inclusive environments for underrepresented students in STEM.

Appendix B: Organizational Chart

Center for Energy Efficient Electronics Science (E^3S)
January 28, 2020



Appendix C: 2019 Summer Research Seminar Attendance

Dates	Faculty	Postdocs	Graduate Students	Undergrad Students	Staff	Teaching Fellows Participants
2019 Summer Seminar Series						
June 27	1	0	4	12	4	2
July 11	1	3	10	22	4	2
July 18	0	0	5	33	4	2

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

E^{3}S Professional Development Program

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

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

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

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

<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^{3}S 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^{3}S 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^{3}S 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 E³S Symposium; presentation at annual retreat, EAB, Site Visit, Journal Club, Research seminar, or E³S Symposium

Proposal Writing
- Attend a proposal writing workshop (1 hour)
- Write and submit proposal on research, education, and diversity activities
- Opportunities: proposal for E³S 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:

Appendix E: TTE REU Recruitment Calendar

Engineering Liaison Conference	October 24, 2019	Berkeley, CA
MESA Student Leadership Conference	October 26, 2019	Sacramento, CA
SACNAS Conference	October 30—November 3, 2019	Honolulu, HI
Bakersfield Community Colleges	November 8, 2019	Bakersfield, CA *(Presented remotely)*
Diablo Valley College	November 8, 2019	
Napa Valley College	November 12, 2019	
Folsom Lake College	November 15, 2019	Folsom, CA
El Camino Community College	December 4, 2019	Torrance, CA
Long Beach Community College	December 4, 2019	Long Beach, CA
Los Angeles Trade Technical College	December 5, 2019	Los Angeles, CA
Los Angeles Harbor Community College	December 5, 2019	Los Angeles, CA
Hartnell College	December 13, 2019	Salinas, CA
TTE Webinars	Wed, Nov 20, 2019 Wed, Dec 11, 2019 Tues, Jan 7, 2020 Mon, Jan 13, 2020	Online

Appendix F: 2019 E^3S Annual Retreat Agenda

10th Annual Retreat
Center for Energy Efficient Electronics Science

September 19-20, 2019
MLK Building
University of California, Berkeley

AGENDA

Day 1 (Morning) – Thursday, September 19, 2019

MLK Building, Tilden Room (5th floor)

Time	Activity / Topic	Speakers
7:30 AM	***Breakfast & Check-In***	
8:00 AM	**Welcome & Introduction**	
	Review of Agenda	
	Goals for the Retreat	**Eli Yablonovitch**
	Center Overview	
8:30 AM	**Theme I: Nanoelectronics**	
	Theme I Overview	**Eli Yablonovitch**
	Progress on Graphene Nanoribbon Project	**Steven Louie**
	Progress on III-V Nanowire Transistor Project	**Jesus del Alamo**
	Progress on 2D Chalcogenide Transistor Project	**Shiekh Zia Uddin**
	Open Discussion	
9:45 AM	***Break & Poster Set-Up***	
10:05 AM	**Theme II: Nanomechanics**	
	Theme II Overview	**Tsu-Jae King Liu**
	Progress on NEM Relay Project	**Junqiao Wu**
	Progress on Squitch Project	**Farnaz Niroui**
	Progress on Stritch Project	**David Zubia (remote)**
	Open Discussion	
11:20 AM	**System Integration**	
	System Integration Overview	**Rawan Naous**
	Open Discussion	
11:50 AM	***Lunch and Poster Session***	

2019 E3S Annual Retreat Agenda

Center for Energy Efficient Electronics Science

10th Annual Retreat
Center for Energy Efficient Electronics Science

September 19-20, 2019
MLK Building
University of California, Berkeley

AGENDA

Day 1 (Afternoon) – Thursday, September 19, 2019

MLK Building, Tilden Room (5th floor)

Time	Activity / Topic	Speakers
1:10 PM	**Theme IV: Nanomagnetics**	
	Theme IV Overview	**Jeffrey Bokor**
	Progress on Ultrafast Magnetic Switching	**Jeffrey Bokor**
	Progress on Spin-Orbit Torque Switching Using Topological Effects	**Xiang Li**
	Spin Currents in Amorphous Materials	**Sayeef Salahuddin**
	Open Discussion	
2:25 PM	***Break***	
2:45 PM	**Theme III: Nanophotonics**	
	Theme III Overview	**Ming Wu**
	Progress on Antenna-Enhanced LEDs	**Ming Wu**
	Progress on Antenna Waveguide Coupling	**Nicolas Andrade**
	Progress on III-V Hetero Epitaxy	**Jeehwan Kim**
	Open Discussion	
4:00 PM	***Walk to Faculty Club*** *(E3S Industry Partners and Faculty)* *or* ***Sutardja Dai Hall*** *(E3S Students and Postdocs)*	
4:30 PM	**Parallel Sessions:** — E3S Faculty and Industry Partners: Feedback & Discussion Meeting (Lewis Room, Faculty Club) — Students and Postdocs: Professional Development Workshop (Room 250, Sutardja Dai Hall)	
6:00 PM	**Wine Reception, Dinner and Recognitions (Faculty Club)**	
	Heyns Room (Faculty Club)	

2019 E3S Annual Retreat Agenda

10th Annual Retreat

Center for Energy Efficient Electronics Science

September 19-20, 2019
MLK Building
University of California, Berkeley

AGENDA

Day 2 (Morning) – Friday, September 20, 2019

MLK Building, Tilden Room (5th floor)

Time	Activity / Topic	Speaker / Facilitator
7:30 AM	***Breakfast***	
8:00 AM	**Center Management**	
	Management, Budget, Preparing for September 2020	**Michael Bartl**
	Open Discussion	
8:30 AM	**Education and Diversity**	
	Education Overview	**Nicole McIntyre**
	Diversity Overview	**Kedrick Perry**
	Open Discussion	
	Diversity Training/Workshop	**Kedrick Perry**
9:45 AM	***Break***	
10:00 AM	**E3S Education Legacy**	
	Breakout Sessions Reporting from Breakout Sessions Open Discussion	**Nicole McIntyre, Michael Bartl** (Moderators)
11:25 AM	**Closing Remarks**	**Eli Yablonovitch**
11:30 AM	***Lunch (boxed)***	
11:30 AM	**Executive Committee ONLY** **ExComm Meeting (1 hour)**	

2019 E3S Annual Retreat Agenda

Appendix G: 2019 Annual Retreat Poster List

LIST OF POSTERS

Pin-Chun Shen, Yuxuan Lin, Cong Su, Christina McGahan, Katherine Aidala, Ju Li, Tomas Palacios, Jing Kong, “Healing of Donor Defect States in Monolayer Molybdenum Disulfide through CVD Oxygen Doping”

Sri Krishna Vadlamani, Tianyao Patrick Xiao, Eli Yablonovitch, “Lineshape and Optimization”

Ilya Piskun, Raymond Blackwell, Erin Brooks, Joaquim Jornet-Somoza, Angel Rubio, Felix R. Fischer, “Nitrogen substitutional doping in graphene nanoribbons”

Fangzhou Zhao, Jingwei Jiang, Ting Cao, Yea-lee Lee, Steven G. Louie, “Topological phases in graphene nanoribbons and metallic graphene nanoribbons”

Shiekh Zia Uddin, Der-Hsien Lien, Ali Javey, “Perfectly Bright Low Dimensional Semiconductors”

Zunaid Omair, Gregg Scranton, Luis M. Pazos-Outon, T. Patrick Xiao, Myles A. Steiner, Vidya Ganapati, Per F. Peterson, John Holzrichter, Harry Atwater, Eli Yablonovitch, “A new thermophotovoltaic record”

Luis M. Pazos Outon, Patrick T. Xiao, Eli Yablonovitch, “Fundamental efficiency limit of lead halide perovskite solar cells”

Xiaoer Hu, Sergio F. Almeida, Zhixin Alice Ye, Tsu-Jae King Liu, “Ultra-Low-Voltage Operation of MEM Relays for Cryogenic Logic Applications”

Zachary Nelson, Jinchi Han, Kosuke Yoshinaga, Jeffrey H. Lang, Vladimir Bulovic, Faranaz Niroui, Timothy M. Swager, “Tuning Squitch Performance Through Molecular Design”

Penghong Ci, Sara Fathipour, Sergio Fabian Almeida, Zhixin Ye, Bivas Saha, Farnaz Niroui, Tsu-Jae King Liu, Junqiao Wu, “Exploring the hysteresis in TMD FETs and NEM relays”

Jinchi Han, Zachary Nelson, Mingye Gao, Jing Kong, Timothy Swager, Farnaz Niroui, Jeffrey Lang, Vladimir Bulović, “Towards High-Performance NEM Switches Based On Tunneling Through Compressible Molecular Junctions (Squitch)”

Rawan Naous, Lazar Supic, Yoonhwan Kang, Ranko Sredojevic, Anish Singhani, and Vladimir Stojanovic, “Tuning Deep Learning Algorithms and Generators for Efficient Edge Inference”

Urmita Sikder, Giulia Usai, Ting-Ta Yen, Kelsey Herron, Mariana Martinez, Louis Hutin, Tsu-Jae King Liu, “BEOL Reconfigurable Interconnects in Standard CMOS Process”

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

Nicolas M. Andrade, Sean Hooten, Seth A. Fortuna, Eli Yablonovitch, and Ming C. Wu, “Efficient Coupling of an Electrically Injected Optical Antenna-LED to a Single-Mode Waveguide”

Sean Hooten, Nicolas M. Andrade, Ming C. Wu, Eli Yablonovitch, “Analysis of Antenna-LED versus Laser Modulation Speed”

Cheng-Hsiang (Jason) Hsu, Niklas Roschewsky, Sayeef Salahuddin, “Spin-orbit torque induced magnetization switching in nano-scale ferrimagnetic GdCo”

Jyotirmoy Chatterjee, Akshay Pattabi, Manel Molina Ruiz, Sayeef Salahuddin, Frances Hellman, Jeffrey Bokor, “Ultrafast helicity independent all-optical magnetization reversal of Co/Pt multilayers coupled with CoGd”

Shehrin Sayed, Cheng-Hsiang Hsu, Sayeef Salahuddin, “Electric-Field Control of Interlayer Exchange Coupling for Magnetization Switching”

Xiang Li, Shy-Jay Lin, Mahendra DC, Chengyang Yao, Wilman Tsai, Shan X. Wang, “Materials Requirements of High-Speed and Low-Power Spin-Orbit-Torque Magnetic Random-Access Memory”

Dennis Toledo, Brayan Navarrete, Mark Stone, Kevin Luongo, Ping Wang, Ping Liang, Sakhrat Khizroev, “A Theoretical Study of Switching Energy Efficiency in sub-10-nm Spintronic Devices”

Tony Vo Hoang, Derek Popple, Scott Meyer, Jeff Cain, Alex Zettl, “Synthesis and Characterization of Zirconium Diselenide Nanoribbons Encapsulated in Carbon Nanotubes”

Alice Wu, Alon Vardi, Jesús del Alamo, “Electrical Characterization of Non-Stoichiometric WOx”

2019 E3S Annual Retreat Agenda

Center for Energy Efficient Electronics Science

Appendix H: 2019 BETR Center Spring Workshop Agenda

betr

Berkeley Emerging Technologies Research Center

Spring 2019 Workshop

Thursday, April 18, 2019

Hearst Mining Memorial Building, Room 290

11:15 AM	*Badge Pickup*	
11:30 AM	*Closed Session for Corporate Affiliates (Working Lunch)*	
	- Opening Remarks	Jeffrey Bokor
	- Corporate Affiliates' Dialog with the BETR Center	*Moderator:* Tsu-Jae King Liu
12:30 PM	*Open Session Begin*	
12:35 PM	Welcome Remarks	Tsu-Jae King Liu
12:40 PM	BETR Presentations (Block 1)	
	- Printed Flexible Devices	Ana Claudia Arias
	- Towards High-Performance Field-Effect Transistors with Atomically Precise Graphene Nanoribbons	Juan Pablo Llinas
	- Computational Microscopy	Laura Waller
1:45 PM	*Break*	
2:00 PM	Industry Presentations and Panel	*Moderator:* Jeffrey Bokor
	- Tom Ni, AMEC - Jan Rabaey, UC Berkeley - Jim Wieser, Texas Instruments - Carlos Diaz, TSMC - Gertjan Hemink, Western Digital	
3:15 PM	*Break*	
3:30 PM	BETR Presentations (Block 2)	
	- Advanced Semiconductor Processing for Monolithic 3D Electronics	Ali Javey
	- Inverse Design of High Efficiency Silicon Photonic Components	Andrew Michaels
	- 3D Sensing	Ming Wu
4:35 PM	Student & Postdoc Poster Session & Reception	
5:45 PM	*Adjournment*	

Appendix I: 2019 BETR Center Fall Workshop Agenda

betr
Berkeley Emerging Technologies Research Center

Fall 2019 Workshop

Monday, October 21, 2019, Hearst Mining Memorial Building, Room 290

ADVANCE AGENDA

10:45 AM	*Registration & Badge Pickup*	
11:00 AM	*Closed Session for Corporate Affiliates (Working Lunch)*	
	- Opening Remarks	Tsu-Jae King Liu
	- Corporate Affiliates' Dialog with the BETR Center	*Moderator:* Jeffrey Bokor
11:55 AM	*Open Session Begin*	
12:00 PM	Welcome Remarks	Tsu-Jae King Liu & Jeffrey Bokor
12:05 PM	BETR Presentations (Block 1)	
	- "Reconfigurable Interconnect Technology for Accelerating AI"	Tsu-Jae King Liu
	- "Accelerating Edge Inference with Algorithms, Architectures, and Devices"	Rawan Naous
	- "Scalable Deep Learning Accelerator Design with Multi-Chip-Module-based Integration"	Sophia Shao
	- "Analog-Based Optimization for Machine Learning and Other Applications"	Eli Yablonovitch
1:25 PM	*Break*	
1:45 PM	BETR Presentations (Block 2)	
	- "Ultrafast Magnetic Switching"	Jeffrey Bokor
	- "Recent work on Ultrathin Ferroelectrics (FE) and Non-Volatile Ferroelectric Memory Devices"	Sayeef Salahuddin
	- "Wearable Sweat Sensors"	Mallika Bariya
	- "Large-Scale Silicon Photonic Switches"	Kyungmok Kwon
3:05 PM	Concluding Remarks	Tsu-Jae King Liu
3:10 PM	*Break*	
3:30 PM	Student & Postdoc Poster Session & Reception	
5:00 PM	*Adjournment*	

Appendix J: 2019 University of Twente Visit Agenda

Center for Energy Efficient Electronics Science

July 16, 2019
Soda Hall 430-8, Wozniak Lounge
University of California, Berkeley

Visit by University of Twente Students/Faculty

July 16, 2019

Soda Hall 430-8, Wozniak Lounge

University of California, Berkeley

Advance Agenda

10:00 AM	Arrival	
10:15 AM	Welcome Remarks	E3S Team
10:30 AM	UC Berkeley and Center for E3S	Michael Bartl
11:15 AM	Marvell NanoLab (Overview)	Allison Dove
12:00 PM	Lunch	
1:00 PM	Graduate Programs at UC Berkeley	Nicole McIntyre
1:30 PM	E3S Student Programs	Kedrick Perry
2:00 PM	Campus Walking Tour	Kedrick Perry, E3S Students
3:00 PM	Departure	

Center for Energy Efficient Electronics Science

Appendix K: California Engineering Liaison Council Agenda

CALIFORNIA ENGINEERING LIAISON COUNCIL

ELC AGENDA
University of California – Berkeley
2594 Hearst Ave, Berkeley, CA 94720
Sutardja Dai Hall, Room 250

Berkeley Engineering

Thursday October 24th, 2019

8:00 am - 9:00 am	Registration and Breakfast	Matthew Sherburne & Tiffany Reardon (Berkeley)
9:00 am - 9:30 am	Welcome / Introductions Welcome from Dean Tsu-Jae King Liu of the College of Engineering at UC Berkeley	ELC Chair Nick Langhoff (Skyline)
9:30 am - 9:45 am	Opening Focus Session	ELC Chair Nick Langhoff
9:45 am–10:15 am	ENGR FDRG Focus Session on ENGR transfer ISMCs, C-IDs, certs	Erik Dunmire (College of Marin) Nick Langhoff
10:15-10:30 am	Break	
10:30 am - 11:15 am	AS-T equivalence strategy	*Nick Langhoff* *Greg Pottie(UCLA)*
11:15 am – 11:30 am	Campus Announcements: Designated time for individuals to share important announcements about their institutions.	*ELC Chair Nick Langhoff*
11:30-1:00 pm	*LUNCH: (290 Hearst Mining)* *Student Poster Symposium*	*Transfer student researchers*
1:00 pm – 2:30 pm	Access, Inclusion, and Workforce Retention of Underrepresented Groups Segment - Programs for Transfer Student Success	*Nick Arnold (Santa Barbara City College)* *Kara Nelson (Berkeley)* *Nicole McIntyre* *Tiffany Reardon* *Meltem Erol*
2:30-2:45 pm	Coffee Break	
2:45-3:30 pm	Service Opportunity Programs	Nick Langhoff Matthew Sherburne Jo-Ann Panzardi (Cabrillo) Anthony St. George (Berkeley)

3:30-5:00 pm	Teaching Techniques Committee (AND IN PARALLEL) Student Affairs (Room TBD) Workshop: The secret sauce to getting into the UC!	*Keith Level (Los Positas)* *Director of Advising and Policy for ESS* *Sharon Mueller & Joey Wong (Berkeley)*
5:00-6:00 pm	Informal Networking Session @ 5:40pm group walk to Jupiter	
6:00-9:00 pm	Happy Hour & Dinner Jupiter Bar in Berkeley	*Matthew Sherburne* *Tiffany Reardon*

Day Two

CALIFORNIA ENGINEERING LIAISON COUNCIL

ELC AGENDA
University of California – Berkeley
2594 Hearst Ave, Berkeley, CA 94720
Sutardja Dai Hall, Room 250

Berkeley Engineering

Friday October 25th, 2019

8:00 am – 8:30 am	Registration and Breakfast	*Matthew Sherburne* *Tiffany Reardon*
8:30 am – 8:45 am	Welcome/Participant Introductions	*ELC Chair Nick Langhoff*
8:45 am – 9:45 am	C-ID / AS-T / FDRG Adoption Procedures for 4-year Colleges Increase C-ID adoption Increase pathway access	*Kate Disney* *Greg Pottie* *Nick Langhoff*
9:45 am – 10:45 am	Segment Meetings: Community College (SDH 250) + ENGR Technology FDRG Update California State University + University of California (SDH 254) *Segments develop action plan to enhance access to engineering courses and shorten time to degree.*	*Vince Bertsch (CCs)* *Jinny Rhee (CSUs)* *Greg Pottie (UCs)*

10:45 am – 11:00 am	Break	
11:00 am – noon	Bylaws Adoption Session	*ELC Chair Nick Langhoff*
noon – 1:30 pm	Working Lunch: ELC Business Meeting Action plan	*ELC Chair Nick Langhoff*
1:30 pm	Adjournment	
1:30 – 2:30pm	Tour of Maker Space at the Library ONR/Teagle meeting (invite only) (1:30 – 3:00pm in 314 Hearst Mining)	*Matthew Sherburne* *Greg Pottie* *Wes Uehara*

Appendix L: 2019 Joint BioEnergy Institute Visit Agenda

JBEI
Joint BioEnergy Institute

Visitors: Transfer to Excellence Summer Research Program (~8 community college students + ~2 chaperones)

POC: Nicole Evans McIntyre, nicolemcintyre@berkeley.edu, 510-664-4882

Organizer: Irina Silva, JBEI, isilva@lbl.gov, Cell: 415-323-9861

Monday, July 15, 3:00 p.m. – 4:30 a.m. | Seminar Room

JBEI, 5885 Hollis St, Emeryville, CA 94608

All guests taking tours of the laboratories at JBEI must wear long pants and closed toe shoes per DOE requirements.

Agenda

03:00 p.m. Arrival & Registration

03:10 p.m. JBEI Overview

Nicole Ing, Post-Doctoral Researcher, Technology Division

03:30 p.m. Q&A

03:40 p.m. Tour of the laboratories

Melanya Gudzeva, Strain Archivist, Operations

Nicole Ing, Post-Doctoral Researcher, Technology Division

04:10 p.m. Final Q&A and Career Discussion

With Melanya and Nicole

04:30 p.m. End

Appendix M: 2019 Student and Postdoc Survey

Year-to-Year Comparison

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

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

		2012	2013	2014	2015	2016	2017	2018	2019
	Total Number of Respondents	20	21	26	29	22	24	22	**16**
	Survey Questions								
Research	The Leadership Team identifies concepts and scientific principles that will enable fundamentally new and different science for digital information processing, in order to achieve a radical reduction in energy consumption in electronic devices.	4.2 ± 0.7	4.4 ± 0.5	4.6 ± 0.6	4.4 ± 0.6	4.3 ± 0.9	4.4 ± 0.6	4.5 ± 1.0	**4.9 ± 0.3**
	The Center is making progress in its research program.	4.2 ± 0.5	4.1 ± 0.9	4.5 ± 0.6	4.4 ± 0.7	4.4 ± 0.9	4.4 ± 0.7	4.6 ± 0.9	**4.7 ± 0.4**
	I understand how my project will contribute to the goals and vision of the Center.	4.3 ± 0.9	4.5 ± 0.6	4.5 ± 0.7	4.6 ± 0.5	4.8 ± 0.8	4.3 ± 0.8	4.3 ± 1.1	**4.7 ± 0.5**
Inclusiveness	The Leadership Team educates a diverse generation of scientists, engineers and technicians to be the future leaders, researchers, educators and workers of low energy consumption device science and technology.	4.1 ± 0.6	4.1 ± 0.8	4.6 ± 0.5	4.3 ± 0.9	4.3 ± 1.0	4.4 ± 0.8	4.5 ± 1.0	**4.8 ± 0.4**
	The Leadership Team provides a research environment that is inclusive of different institutions, research themes, science and engineering disciplines, and individual differences.	4.1 ± 0.6	4.0 ± 0.9	4.7 ± 0.5	4.6 ± 0.6	4.5 ± 0.7	4.5 ± 0.6	4.5 ± 0.9	**4.8 ± 0.4**

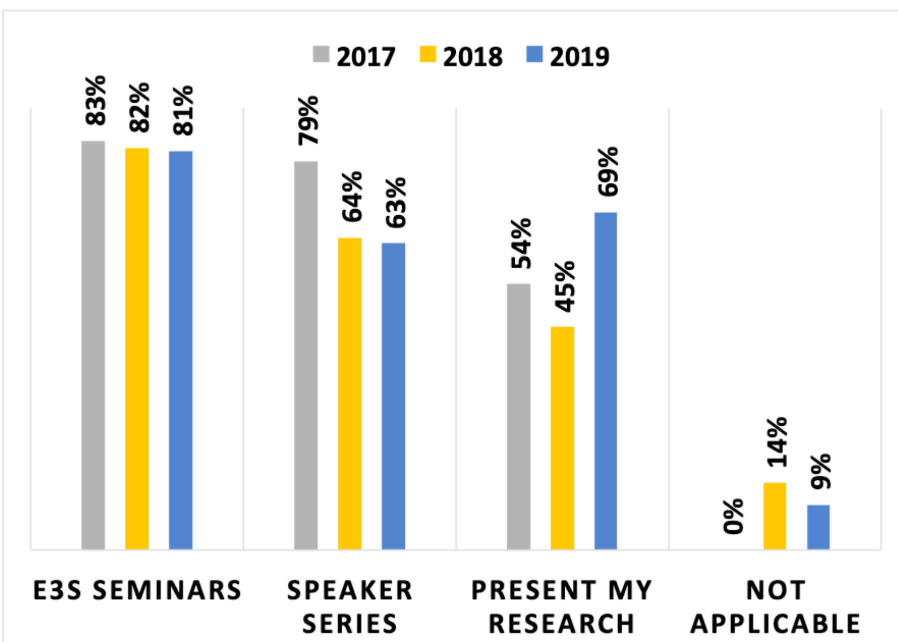
Center for Energy Efficient Electronics Science

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

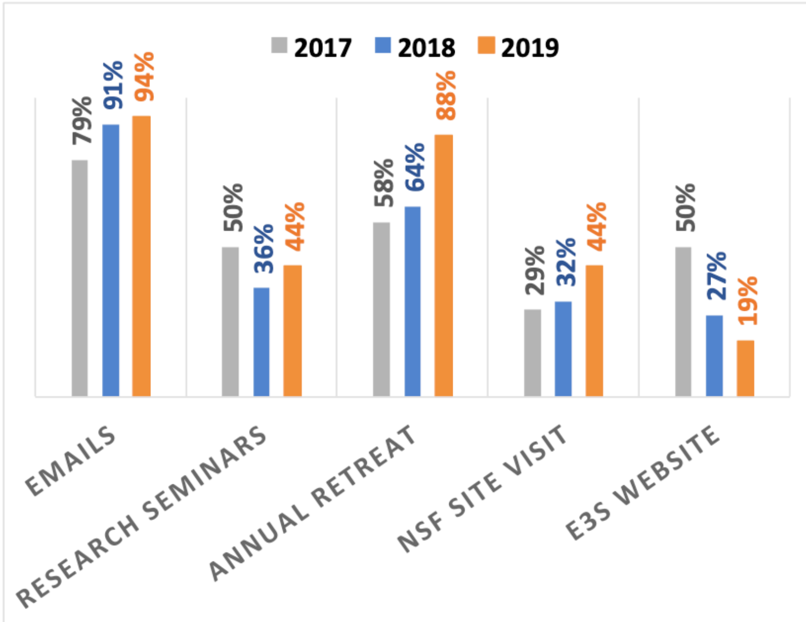
Performance Focus	The Leadership Team promotes a culture permeating the Center's relationships, processes, and activities that recognize and values performance, and avoids possessiveness.	3.9 ± 0.9	4.1 ± 0.7	4.5 ± 0.6	4.3 ± 1.0	4.3 ± 0.9	4.3 ± 0.6	4.3 ± 1.0	**4.8 ± 0.4**
	The Leadership Team is recognizing and evaluating me on my performance.		3.8 ± 1.0	4.4 ± 0.7	4.0 ± 1.0	4.1 ± 1.0	4.0 ± 0.9	3.6 ± 1.3	**4.3 ± 0.8**

Part B: Effectiveness of the Center's Activities

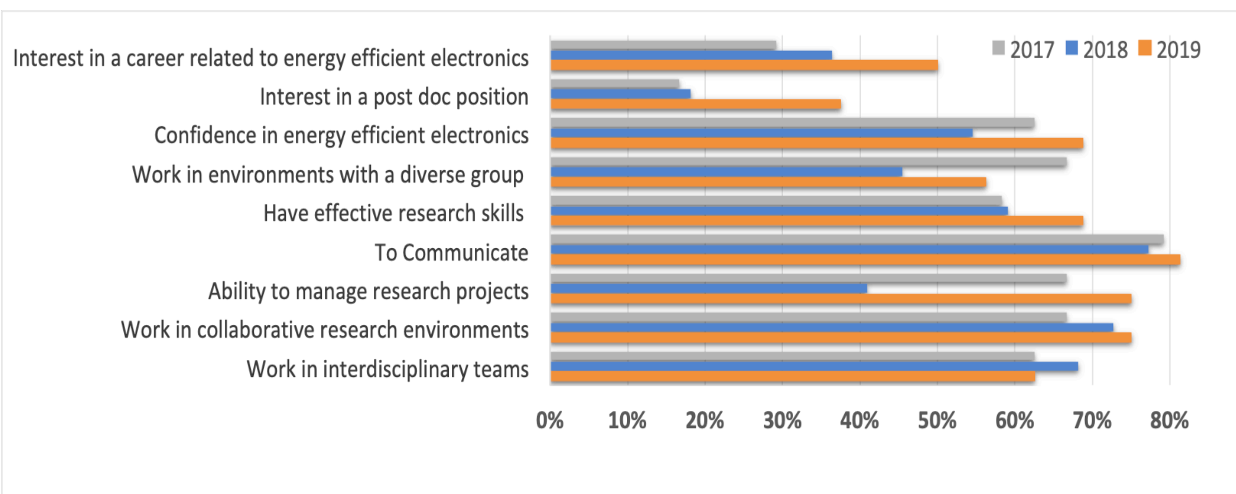
1. Respondents indicated the following activities are sharpening their understanding of low energy consumption device science and technology.



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

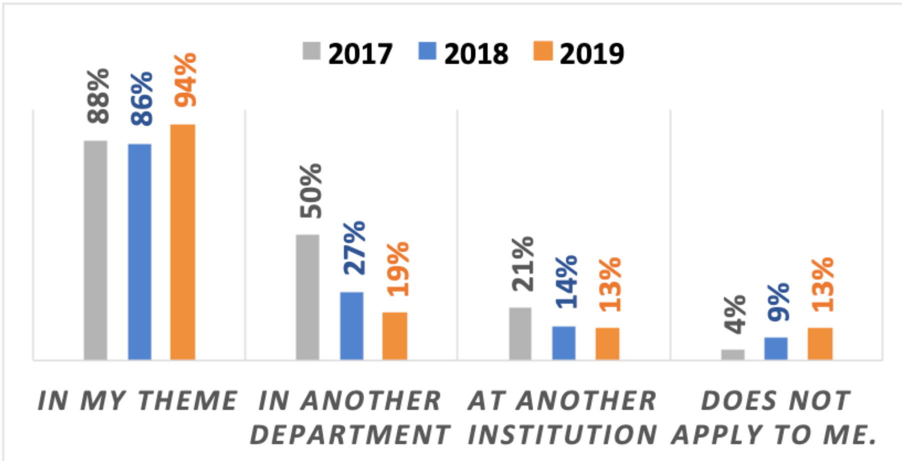


3. Respondents identified the following areas were positively impacted as a result of their experience at E[3]S.

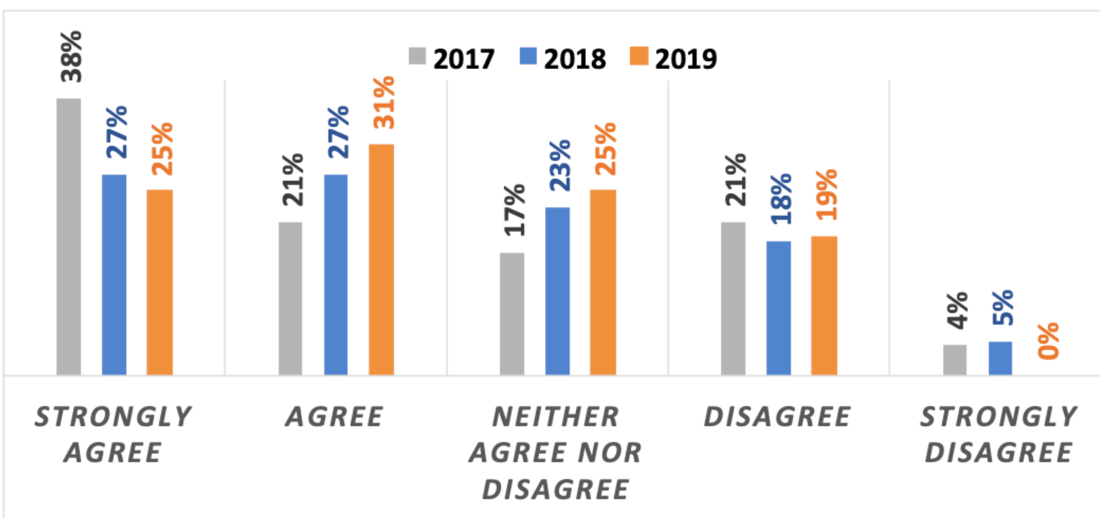


Part C: State of Collaborations

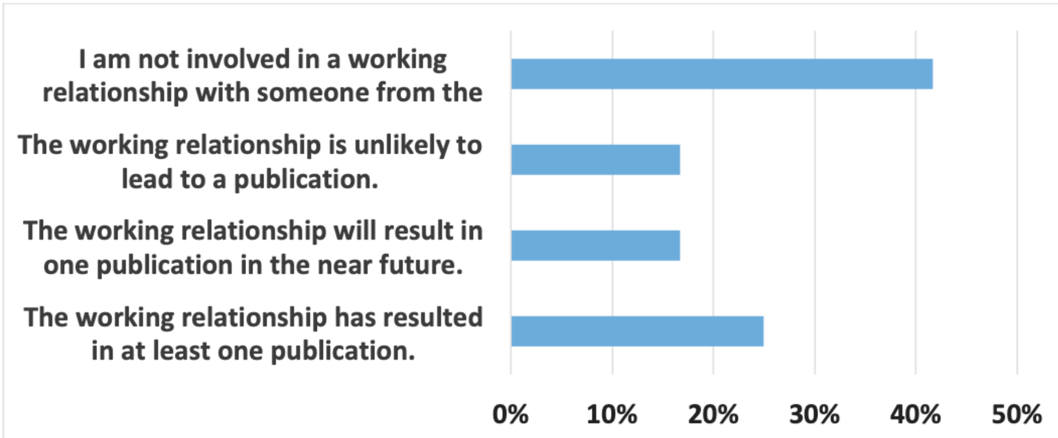
1. Respondents indicated that the following people helped with their E^3S research.



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



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



Part D: Ethics

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

Appendix N: 2019 E^{3}S Faculty Survey

Year-to-Year Comparison for Last Five Years

Leadership Survey

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

The E^{3}S leadership team is dedicated to:	**2015**	**2016**	**2017**	**2018**	**2019**
Creating an inclusive work environment.	4.9±0.2	4.9±0.2	4.8±0.4	4.9±0.3	**4.7±1.0**
Promoting a work environment that values and encourages teamwork.	4.9±0.3	4.9±0.2	4.8±0.4	4.9±0.2	**4.7±1.0**
Providing open and timely communication to me.	4.7±0.6	4.8±0.4	4.8±0.4	4.8±0.4	**4.6±1.0**
Recognizing and evaluating me on my performance.	4.7±0.6	4.3±0.8	4.7±0.6	4.7±0.4	**4.5±1.0**
Making decisions that are in the best interest of the Center.	4.8±0.4	4.8±0.4	4.8±0.4	4.8±0.4	**4.7±1.0**
Providing opportunities to collaborate.	4.9±0.3	4.8±0.4	4.8±0.4	4.9±0.3	**4.7±1.0**
Providing tools that facilitate collaboration.	4.6±0.6	4.7±0.5	4.7±0.6	4.8±0.4	**4.4±1.0**
Educating a diverse generation	4.9±0.3	4.9±0.3	4.8±0.4	4.9±0.3	**4.6±1.1**
Identifying fundamentally new concepts and scientific principles	4.9±0.2	4.8±0.4	4.8±0.4	4.9±0.2	**4.7±1.0**

2019 sampling size: 15

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

Center for Energy Efficient Electronics Science