FOR PUBLIC

Center for Energy Efficient Electronics Science

Final

Period 6 Annual Report

Submitted on

February 5, 2016

A National Science Foundation Science & Technology Center

(Award ECCS - 0939514)

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	February 9, 2017
Reporting period	March 1, 2016– February 28, 2017
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
Contact Information	
Address	267M Cory Hall Berkeley, CA 94720-1770
Phone Number	510-642-6821
Fax Number	510-666-3409
Email Address of Center Director	eliy@eecs.berkeley.edu
Center URL	https://www.e3s-center.org

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 Vladimir Bulović
Address	77 Massachusetts Avenue, 13-3138 Cambridge, MA 02137
Phone Number	617-253-7012
Fax Number	617-258-0666
Email Address of Center Director	bulovic@mtl.mit.edu
Role of Institution at Center	MIT is a lead research, education, and outreach partner.

Institution Name	Stanford University H.-S. Philip Wong
Address	420 Via Palou Stanford, CA 94305
Phone Number	650-725-0982
Fax Number	650-725-7731
Email Address of Center Director	hspwong@stanford.edu
Role of Institution at Center	Stanford is a lead research, education, and outreach partner.

Institution Name	The University of Texas at El Paso David Zubia
Address	500 West University Ave El Paso, TX, 79968
Phone Number	915-747-6970
Fax Number	915-747-7871
Email Address of Center Director	dzubia@utep.edu
Role of Institution at Center	The University of Texas at El Paso is a research, education, and outreach partner to encourage greater minority participation in engineering.

Institution Name	Florida International University Sakhrat Khizroev
Address	10555 W. Flagler Street, EC 3955 Miami, FL 33174
Phone Number	305-348-3724
Fax Number	305-348-3707
Email Address of Center Director	khizroev@fiu.edu
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
Address	1102 Q Street, Suite 4450, Sacramento, CA 97811
Phone Number	916-322-6881
Fax Number	N/A
Email Address of Center Director	pwalker@cccco.edu
Role of Institution at Center	California Community Colleges Chancellor's Office represents the California Community College system whose multiple member campuses are education and outreach partners to encourage greater women, minority and first generation college student participation in science, engineer and mathematics.

1b. Biographical Information of New Faculty

Please see Appendix A for biographical information on two new faculty members. While both new members (Jing Kong and Steven Louie) formerly joined the Center at the end of Period 6, they started their research efforts at the beginning of Period 7.

1c. Primary Contact Person

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

Name of the Individual	Michael H. Bartl
Center Role	Executive Director
Address	552 Sutardja Dai Hall, Berkeley, CA 94720
Phone Number	510-664-7814
Fax Number	510-664-4113
Email Address	mbartl@berkeley.edu

2. *Context Statement*

The NSF Science and Technology Center for Energy Efficient Electronics Science (E^3S), now entering its seventh year, continues to address energy consumption in information processing through broad research and technology, encompassing engineering, physics, chemistry, and materials science. With rapidly increasing demand for information processing speed and bandwidth, the need for such a broad-based multi-disciplinary and multi-institutional scientific endeavor is as important now, as it was in 2010, when the Center for E^3S was founded.

This rapid growth in the demand for information processing speed and bandwidth is driven by recent advancements in cloud computing, social networking, mobile internet, and data analytics. Accompanying this growth is an increased importance of wireless sensor swarms, body-centered networks, data centers and servers, and supercomputers. Information processing consumes a significant fraction (4%) of the total electricity production in the United States, a growing burden. Energy efficiency will lead to increased cybernetic functionality.

Fundamentally, there is enormous room for improvement of energy efficiency of electronic systems, since the energy used to manipulate a single bit of information is currently about 100,000 times greater than the theoretical limit. In order to address this issue, there is a critical need for fundamental and conceptual breakthroughs in the underlying physics, chemistry, and materials science that form the foundation of information-processing technologies. The Center for E^3S has been targeting this very challenge and seeks to approach the fundamental physical limits of electronic devices, circuits and systems for digital information-processing technologies. Now in its seventh year, the Center for E^3S has made significant contributions in the development of next-generation ultralow energy switching concepts. This was achieved by identifying barriers, revolutionary concepts and scientific principles that would enable transformative and fundamentally new and different digital-information processing science. The defining goal remains to achieve a radical increase in energy efficiency and functionality.

The defining research goal of the Center for E^3S is to provide the science and fundamental knowledge needed for developing electronic systems approaching the theoretical limits. This ambitious goal is being pursued through a collaborative approach, involving engineers, chemists, physicists, and materials scientists from the University of California, Berkeley (*Berkeley*), Massachusetts Institute of Technology (*MIT*), Stanford University (*Stanford*), The University of Texas at El-Paso (*UTEP*), and Florida International University (*FIU*). These five core institutions work in close collaboration with various community colleges, as represented by the California Community College System's Chancellor's Office, and with industrial partners Applied Materials, IBM, Intel, Hewlett Packard Enterprise, and Lam Research.

From its inception, the Center for E^3S has conducted research in four distinct but interrelated themes, with the scientific focus toward two fundamental issues in digital information processing systems: (1) a low voltage digital logic switch, which would reduce the energy cost of wired communication, and (2) more efficient short-range optical communication. The four interrelated themes are: (I) Nanoelectronics: Solid-state millivolt switching; (II) Nanomechanics: Zero-leakage switching; (III) Nanophotonics: Few-photon optical communication; and (IV) Nanomagnetics: Low-energy fast magnetic switching. Overarching these four research themes is Systems Integration, which checks that the new scientific device concepts would actually lead to new energy-efficient system architectures. Themes I, II and IV pursue different approaches to ultralow-energy switching allowing more efficient wired communication, while theme III addresses short range optical communication, intra-chip as well as short range chip-to-chip. System Integration research is targeted to ensure that the component research outcomes of the Center will be effective in enabling future ultra-low energy information systems.

Current logic switching technology depends on the conventional transistor, which for all its success in forging today's interconnected society, suffers from a serious drawback: **The conduction of conventional transistors is thermally activated** and this mechanism is rather insensitive, requiring powering voltages of ~0.8 Volt to provide a good On/Off ratio, even as transistors become smaller and smaller. The wires connecting the transistor, however, could operate with a very good signal-to-noise ratio, even at voltages <8 milli-Volt. Since energy consumption is proportional to the square of operating voltage, the energy currently used to manipulate a single bit of information is 4 orders of magnitude higher than the theoretical limit. Therefore, **a more sensitive, lower-voltage switch is needed** as a successor to the conventional transistor.

The Center for E^3S researchers recognized early on that a new ultra-low energy switch must meet a set of key specifications to be of practical use. The three most important specifications are:

- Steepness (or sensitivity): ~1 mV/decade; to enable switching with a swing of only a few milli-Volts
- On/Off conductance ratio: ~10^6:1; 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 milli-Siemens/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 1Volt, the corresponding switch conductance requirement becomes 1mS/µm rather than the more conventional given requirement 1mA/µm.)

Additionally, for the Center's optical communication research efforts the goal is to replace metal wires with optical interconnects, that lowers the photons/bit by several orders of magnitude from its current value, ~20000 photons/bit; ultimately, approaching the quantum limit, ~20 photons/bit.

Research Strategic Plan & Rationale

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 is aligned to the following theme strategies and approaches, which have remained in Period 7.

Theme I: Nanoelectronics

Led by **Eli Yablonovitch** (*Berkeley*), the goal of the nanoelectronics theme has been to develop a semiconductor switch sensitive enough to be actuated by milli-Volts, and thus orders of magnitude more efficient than conventional transistors. Among possible alternative switching mechanisms, tunnel transistor action has emerged as the most inevitable candidate at the nanoscale. Despite continuing optimistic theoretical predictions regarding the steepness, On/Off ratio and conductance of tunnel transistors [1], experimental research around the world has failed to produce devices fulfilling the requirements.

There are two accepted tunnel switching mechanisms, tunnelling-distance modulation and density-of-states modulation, which is also sometimes called energy filtering. Energy filtering is the desired modulation mechanism, since it projects toward high conductance in the On-state. Unfortunately, state-of-the-art device results have continued to be disappointing and are more characteristic of the less desirable tunnel-distance-modulation mechanism. Leading results show that modulation is steep at low currents [2-5], but rather insensitive at the high conductance (current) density needed for acceptable clock speed. Averaged over both low and high current density, under the tunneling-distance-modulation mechanism, a ~50 percent reduction in operating voltage might be achievable.

Since the goals of the Center for E^3S are far beyond a 50 percent reduction of the operating voltage, and are aimed ultimately at milli-Volt switching, nanoelectronics researchers at E^3S have focused on elucidating the underlying device physics, which could lead to orders of magnitude energy reduction, as opposed to simple device optimization. Guided by theme leader **Eli Yablonovitch** (*Berkeley*), E^3S nanoelectronics theme researchers at Berkeley and MIT have shed light on why previous attempts to design and fabricate tunnel switches operating on the preferred density-of-states mechanism have failed [6,7]: In short, this mechanism demands higher materials interface perfection than ever previously required or achieved in solid-state electronics.

In Period 7 the goals of the nanoelectronics research theme of the Center for E^3S have been to (1) gain in-depth understanding of interfacial effects and trap-assisted tunneling, and (2) search for new material systems with ultra-low interfacial defect density. It should be emphasized that two new faculty investigators started their research efforts toward the search for new semiconductors at the beginning of Period 7: Prof. **Jing Kong** (*MIT*) and Prof. **Steven Louie** (*Berkeley*). Both of them have already substantially contributed to the nanoelectronics theme.

Regarding the first goal, the **Yablonovitch** group and the **Antoniadis** and **del Alamo** groups (both *MIT*) continued to perform detailed studies of trap-assisted tunneling at both the modeling and experimental level. The model system used in these studies are vertical nanowire tunnel transistor structures fabricated at MIT. Current experimental goals are to reduce the semiconductor nanowire diameter to achieve single-channel III-V vertical nanowire tunnel transistors, which would expose the physics of individual defect states. The experimental current-voltage data would elucidate the two-step leakage process, thermal activation followed by band-to-band tunneling discovered in the last period.

The second and more important research topic of the nanoelectronics theme is the search for new material systems with ultra-low interfacial defect states with the goal to achieve density-of-state switching modulation tunnel transistors with high On/Off ratios and steep modulation, even at high conductance (current) densities. In this regard, the nanoelectronics theme has intensified research in both two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs) as potentially low-defect density semiconductors.

The 2D-TMDC research efforts, led by Berkeley researchers **Ali Javey** (*Berkeley*) and **Eli Yablonovitch,** has been strengthened by the addition of **Jing Kong**. The current goals was to extend the superacid "defect-healing" method developed in the Javey group [8] to new CVD grown 2D-TMDC samples, to characterize new TMDC materials with very low defect densities, devise methods for bottom-up growth of high-quality TMDC layers, and integrate these 2D semiconductors into device structures.

The Center's efforts in the bottom-up synthesis of graphene nanoribbon semiconductors, which can potentially be purified by chromatography to remove defective molecular structures has been led by organic chemist, **Felix Fischer** (*Berkeley*). These structures are unlike semi-metallic graphene in that they exploit lateral quantum confinement to produce a bandgap in the narrow one-dimensional nanoribbons. Current goals of this project focus on the design and incorporation of molecularly synthesized quantum dots incorporating narrow tunneling barriers as a means to control electrical switching. These efforts are supported by theoretical physicist, **Steven Louie** (*Berkeley*), with first principles quantum mechanical calculations, with **Eli Yablonovitch** providing device guidance toward the rational design of functional switches relying on quantum tunneling.

Theme II: Nanomechanics

Led by **Tsu-Jae King Liu** (*Berkeley*), the goal of the nanomechanics theme has been to demonstrate reliable nano-electromechanical (NEM) switch (or relay) operation at or below 10 mV. A further major aim is to demonstrate feasibility of this approach in a system application. Typically, mechanical switches conduct current when two plates are in contact, and turn off current when the plates are separated. Since mechanical switches inherently have zero off-state current, they are promising solutions for the off-state leakage issue. Realizing that surface adhesion ultimately limits relay scaling, the Center has focused on new approaches that go beyond voltage reduction through scaling and new device design. Instead, E^3S nanomechanics researchers pursue the concept of a tunneling relay whereby the electrical activation will occur when the two electrodes are brought into close proximity, but do not touch each other. The spacing of the electrodes can be controlled by non-pull-in-mode operation or by folding molecular chains. The latter approach constitutes a molecular squeeze-switch, or "Squitch" [9]. In addition, the theme has recently developed the "Stritch" concept (short for stretch-switch), a piezoresistive NEM switch by straining 2D chalcogenide layers using electromechanical actuators.

In Period 7, the main goal of the nanomechanics research has been to continue to lower the contact adhesion energy of electromechanical switch designs using different approaches. The **King Liu** group has focused on the minimization of hysteresis voltage of electro-mechanical switches (relay) through new device design allowing for non-pull-in-mode operation. The goal is to minimize contact adhesion energy since contact stiction gives rise to hysteresis voltage, which, in turn, limits minimization of the operating voltage of an electromechanical switch. In collaboration with the **Junqiao Wu** (*Berkeley*), the **King Liu** group has also explored application of anti-stiction molecular electrode coatings in the form of self-assembled monolayers.

The latter approach has some similarities with the squitch concept, which is pursued by the groups of **Jeffrey Lang**, **Vladimir Bulovic** and **Timothy Swager** (all at *MIT*). In this switch, the vertically-movable source is supported by a molecular monolayer that is compressed upon application of a gate-source voltage, thereby permitting source-drain electron tunneling. The goal is to develop a switch in which the molecular monolayer: (1) defines the switch gaps; (2) provides a scaffolding to support the movable source and a spring to restore its position upon removal of the gate-source voltage; and (3) prevents direct metal-metal source-drain contact thereby alleviating stiction problems.

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 **King Liu** and **Javey** groups (both *Berkeley*). In this device the stretching of the semiconductor chalcogenide material by electromechanical actuators causes straining of a 2D chalcogenide layer. This causes tensile strain and concomitant change in the chalcogenide bandgap and conductivity.

Vladimir Stojanovic (*Berkeley*) has been leading the system integration efforts of the nanomechanics theme with the goal to (1) provide a path to quantifying the benefits of the emerging device technologies at the circuit/system level and (2) give guidance to the device designers by identifying which device design parameters are of critical importance to improve properties at the system level. The goal is to create circuit-level device models that are versatile-enough to capture the most important characteristics of the underlying devices yet simplified-enough to enable fast circuit-level simulation. Current efforts focus on analyzing the application of NEMory relays in creating dense, low-energy nonvolatile memory (NVM) arrays with pattern-matching capabilities, in collaboration with the **King Liu** group.

Theme III: Nanophotonics

Led by **Ming C. Wu** (*Berkeley*), the goal of the nanophotonics theme is to address the increasing energy requirements of communication which dominates information processing. In fact, most of the energy in data processing is related to charging and discharging the communication wires of conventional chips. The aim of theme III is to replace conventional wires with optical waveguides, such as silicon photonics, to enable on-chip optical communications at unprecedented low energy levels. Current systems require a minimum of around 20,000 photons per bit of information transfer. Given that the quantum limit of photons-per-bit in a data-link can be as low as 20 photons/bit, there is an enormous opportunity for energy reduction. E^3S nanophotonics researchers have been pursuing the ultimate goal of approaching this quantum limit, within the constraints of short range communications. To meet this goal, theme III researchers recognized early on that energy efficiency and sensitivity of both the light emitter and the photo-receiver system need to be revolutionized.

On the emitter side, the E^3S nanophotonic researchers identified spontaneous emission from antenna enhanced nanoLEDs to be faster and more energy efficient than the stimulated emission of lasers, which are currently the ubiquitous light source in optical communications [10]. Led by the research groups of **Ming Wu** and **Eli Yablonovitch** (both *Berkeley*), major advances toward this goal have recently been achieved by demonstrating spontaneous emission enhancements of more 300 times under optical excitation. Moreover, >100-times acceleration in the spontaneous emission rate has also been achieved under direct electrical-excitation [11,12]. The first time that antenna spontaneous emission enhancement has been observed under electrical injection, reaffirming the nanophotonics theme's strategy of introducing optical antenna enhanced spontaneous light emitters for energy-efficient short distance on-chip optical interconnects.

Current goals include to further improve antenna-enhanced LED performance under electric-excitation through a collaborative effort by the groups of **Eugene Fitzgerald** (*MIT*) and the *Berkeley* research groups of **Ming Wu** and **Chang-Hasnain**. For this, new epitaxial InGaAs/InGaAsP LED structure wafers have been designed by the **Wu** group and grown by the **Fitzgerald** group by MOCVD. The **Chang-Hasnain** group is developing a method for providing an adequate photon emission rate from these nanoscopic LEDs.

At the systems level, the Center has recognized that photo-receiver research is of equal importance to the novel antenna-LED transmitter. Systems analysis by **Vladimir Stojanovic** (*Berkeley*) in collaboration with **Eli Yablonovitch** and **Ming Wu** revealed that a more sensitive photo-receiver concept is needed. Short on-chip optical communications links require simple direct detection. In this period, a new first principles analysis of the physics and circuit principles required for sensitive direct detection was performed, identifying new opportunities for improvement, that is also likely to be adopted by the silicon photonics industry. Among the requirements, unsurprisingly, the photodetector must be very small and have the lowest possible capacitance. As part of the Center's integrated systems level approach, we have found furthermore that significant changes must be adopted within the opto-receiver circuitry. Center director, **Eli Yablonovitch** has presented this parallel solution to the silicon photonics industry representatives, who appear to be poised to adopt these innovations, which would greatly improve silicon photonics data throughput and reduce the all-important energy/bit. If this serendipitous technology spinout occurs, that will be one of the important successes of the Center for E^3S.

Theme IV: Nanomagnetics

Led by **Jeffrey Bokor** (*Berkeley*), the goal of the nanomagnetics theme has been to use current-driven magnetic elements for electrical communication and switching at sub-femto-Joule energies, and with fast switching speeds as low as <10 picoseconds. To achieve this, the nanophotonics theme takes advantage of newly discovered ultra-sensitive, current-driven switches employing actuated spin-orbit torque (spin-Hall effect) to switch a magnet [13]. Such a component can have current in/current out gain, as well as fanout. 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.

A current goal of the nanomagnetics group is also to utilize a newly discovered helicity-independent optical pulse-induced ultrafast magnetic switching in the picosecond range in the ferrimagnet GdFeCo. While the initial work needed excitation with laser pulses of only 55 femtosecond width [14], E^3S researchers **Jeffrey Bokor** in collaboration with **Sayeef Salahuddin** (both *Berkeley*) have extended this approach to electrical pulse excitation with pulses as long as 10 picoseconds. This is a completely new mechanism of magnetic switching and opens the door to on-chip operation using conventional CMOS electrical pulses. To pursue this goal, a new collaboration has been initiated between the **Bokor** group and the group of **Philip Wong**

(*Stanford*) to integrate magnetic device structures with advanced CMOS chips in order to test magnetic switching triggered by electrical pulses generated directly by CMOS circuits.

The **Salahuddin** group continues work on understanding the fundamental nature of spin transport and spin angular momentum transfer in spin-orbit coupled heterostructure. Specifically, the goal of this work is to gain insights into the physics of spin current generation through spin orbit coupling and identify potential ways to increase the efficiency of current induced magnetic switching. In the current period, the goal moved to investigating switching of ferrimagnets rather than conventionally used ferromagnets since the former have the potential to both reduce the amount of current needed for switching and increase the speed of switching from nanoseconds to tens of picoseconds. The goal of exploiting the new physics in magnetic tunneling junction devices with planar sizes in the sub-5-nm range has been pursued by **Sakhrat Khizroev** (*FIU*) and the **Bokor** group. In this size range, surface effects dominate over volume effects and collective spin effects play a key role, determining the energy needed to switch spin states. Modeling showed the potential of extremely large ON/OFF ratios due to a significantly improved spin filtering in such a small size range.

A new research project aimed at in-memory and normally-off computing using magnetic nonvolatile devices, which started in the previous period by a collaboration between the **Bokor** and **Salahuddin** groups with **Vladimir Stojanovic** (*Berkeley*), has intensified this period with the transition of **Philip Wong** into the nanomagnetics group. The goal of this project is to reduce the power consumption of computers by turning off large portions of the computer that are not in use. The use of nonvolatile memory can make normally-off computing viable, since the shut-down part of the computer can be restored into its original state (once it is needed) without needing to write to or read from external storage. By distributing the memory over the circuit (memory-in-logic), additional power savings due to reduced interconnect length can be achieved.

Education & Diversity Strategic Plan

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

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

Graduate Education

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

Undergraduate Education

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

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

The Center has relied on the latter two programs to build a diverse pipeline for graduate school and into the Center. In particular, the Center chose a California community college focus because the California community college system is the largest in the US and these schools have traditionally been the preferred first stop in undergraduate education for women, underrepresented minorities, and first generation college students. After five years of operation, the Transfer-to-Excellence (TTE) program has enabled not only higher transfer rates of California community college students to STEM baccalaureate programs, but has enabled its participants to transfer to top four-year institutions. TTE alumni, who were interns in the laboratories of E^{3}S or E^{3}S affiliated faculty, have been transferring to four-year institutions since Fall 2012 at a rate of 96%, with most transferring to Tier 1 academic institutions. Prompted by the E^{3}S External Advisory Board, the Center conducted a study in Period 7 that is intended to measure the self-efficacy of TTE students before and after the program, comparing the TTE interns with those applicants who were not accepted. The study informs that the TTE community college students reported a significantly higher level of confidence in pursuing a STEM education, and their self-efficacy reporting increases by the end of the summer, while non-TTE interns have self-efficacy rates similar to TTE students at the beginning of the summer.

The recruiting of underrepresented groups including women and racial minorities is emphasized across the spectrum of the education programs. Furthermore, the Center is concerned with improving access and supporting first-generation college students, veterans, persons with disabilities, and those from lower income backgrounds to be able to successfully transition to an academic environment or the STEM workforce. While the rate of students entering graduate school among the E^{3}S REU program alumni is high (69%), the rate that students are transferring into the Center is still somewhat low. Even though a substantial percentage of alumni continue their graduate degree at an E^{3}S member institution, they do not pursue a thesis in an E^{3}S area of research. The Center recognized this difficulty and has addressed the challenge through hiring and managerial changes. In Period 6, the E^{3}S Executive Committee decided to separate the management of the function of Education and Diversity. Now, the Center has an Education Manager, who is responsible for Education, and a Diversity and Outreach Director who is responsible for Diversity.

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

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

Online Education

The Center looks to build its education legacy with online education and training materials that relate to the Center's research focus. This strategy was adopted in the Center's 4th year. This strategy is expected to impact all levels: developmental experiences for the Center' graduate students, postdocs, and staff, as well as educational resources and knowledge transfer venue for a wide range of audiences. A 1.5-hour mini-course in Energy Efficient Electronics for entry level graduate students has been in development. Also in development is an e-book that is geared towards a high-school audience. The Center will have completed an outline for this book by the end of Period 7, and will be drafted during Period 8.

Knowledge Transfer

Knowledge transfer is central to E^{3}S and a key metric of its success. The Center regards knowledge transfer as a two-way street by establishing partnerships that will accelerate the Center's research and programmatic endeavors, while creating new knowledge that can be shared with industry, academia and research labs. The Center's knowledge transfer strategy involves all of the E^{3}S industry and education partnerships to serve as venues for introducing new and more efficient electronics technologies. As the Center's research results lead to changes in directions and approaches, it is critical that the Center's sharing of knowledge will lead to a community of like-minded research peers who together can accelerate the achievement of the goal of milli-Volt switching and few-photon communications.

Recognizing that education is itself an important knowledge transfer element, the Center prepares its students and postdoctoral members to be the next generation knowledge transfer practitioners, who will have opportunities to communicate science to audiences at all levels.

The preparation of the next generation of scientists, engineers and technicians is also a community endeavor. The Center leverages the expertise and resources of its partners to deliver on the Center's 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^3S Performance in Period 7

In this section, a summary of the progress of the Center for E^3S in Period 7 is presented. Details and in-depth analyses of the results are given in the following sections of this report.

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

Table 1.1. Center for E3S Performance Targets and Results

Objective	Metric	Targets	Results					
			P 2	P 3	P 4	P 5	P 6	P 7
Research	Multi-PI projects	Period 2: 30%	44%	67% (14)	55% (12)	64% (14)	65% (11)	79% (15)
		Period 5: 75%						
		Period 6: 50%						
		Period 7: 60%						
	Multi-Institutional projects	Period 2: 10%	4%	10% (2)	9% (2)	23% (5)	29% (5)	32% (6)
		Period 5: 30%						
		Period 6: 15%						
		Period 7: 20%						
	Publications with authors from multiple institutions	Period 3: 12	0	1	1	1	3	4
		Period 4: 3						
		Period 5: 5						
		Period 6: 5						
		Period 7: 5						
	New joint research funding awards	Period 6: 1	(new for P6-10)				0	3
		Period 7: 0						
Education	Center graduates completed E^3S training	Period 2: Baseline	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)
		Period 3: 50%						
		Period 4: 50%						
		Period 5: 50%						
		Period 6: 15%						
		Period 7: 30%						
	Students accessing online courses of the Center	Period 6: 50	(new for P6-10)				0	0
		Period 7: 75						
		Period 3: 5%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)	36 (69%)

	Undergraduates who pursue advanced degree in science and engineering	Period 4: 30% Period 5: 35% Period 6: 40% Period 7: 45%						
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80% Period 6: 85% Period 7: 85%	n/a	3 (100%)	6 (100%)	7 (100%)	6 (100%)	4 (80%)
	Pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline Period 4: 70% Period 5: 70% Period 6: 80% Period 7: 80%	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)
	Students and postdocs serving in leadership roles in the Center	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Period 6: 30% Period 7: 30%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)
Diversity	Women in the Center's research programs	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 20% Period 6: 25% Period 7: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)
	Underrepresented minorities in the Center's research programs	Period 2: baseline Period 3: 15% increase Period 4: 5% Period 5: 10% Period 6: 10% Period 7: 12%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)

	Participants from underrepresented* groups in the Center's Diversity programs	Period 3: Baseline	n/a	93 (82%)	Women:	Women	Women	Women
		Period 4: 80%			37 (44%)	26 (41%)	29 (40%)	25 (40%)
		Period 5: 85%			URM:	URMs	URMs	URMs
		Period 6: 85%			58 (68%)	36 (56%)	49 (67%)	38 (60%)
		Period 7: 85%			**Total:**	**Total**	**Total**	**Total**
					73 (86%)	**49 (77%)**	**66 (90%)**	**63 (87%)**
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center	Period 6: 40%	(new for P6-10)				17 (55%)	23 (54%)
		Period 7: 45%						
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate	Period 6: 85%	(new for P6-10)				16 (70%)	22 (81%)
		Period 7: 85%						
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering	Period 6: 80%	(new for P6-10)				73 (55%)	102 (63%)
		Period 7: 80%						
Knowledge Transfer	Center publications	Period 2: 18	17	17	19	39	45	41
		Period 3: 18						
		Period 4: 18						
		Period 5: 18						
		Period 6: 25						
		Period 7: 25						
	Talks at peer-reviewed conferences	Period 6: 12	(new for P6-10)				14	12
		Period 7: 12						
	Center sponsored symposia & workshops	Period 2: Baseline	1	0	1	0	1	1
		Period 3: 0						
		Period 4: 1						

		Period 5: 0 Period 6: 2 Period 7: 1						
	External citations of publications *(cum)*	Period 3: 10 Period 4: 100 Period 5: 100 Period 6 - 10: 25% increase	15	178	393	719	1724	2718
	Contacts with industry:							
	• Talks & Meetings	All Periods: 36	66	20	42	62	35	42
	• Industry Presentations	All Periods: Yearly: 2	4	2	6	3	5	2
	Research collaboration with industry	Period 4: 1 Period 5: 2 Period 6: 3 Period 7: 3	0	1	1	4	6	8
	Patent disclosures							
	• Disclosure/Provisional	Period 3: 3 Period 4: 3 Period 5: 5 Period 6: 2 Period 7: 2	1	0	1	0	2	1
	• Patent Application Filed	Period 4: 0 Period 5: 3 Period 6: 1 Period 7: 2	1	0	0	0	4; 1 granted	4; 2 granted
	Technologies attributable to Center's research		(new for P6-10)				0	0
	• Low energy devices	Period 6: 0 Period 7: 0						
	• Enabling other applications	Period 6: 0 Period 7: 0						
	Center's alumni into relevant industries	Period 5: 50%	Students: 0%	Students: 64% (7)	Students: 16% (2)	Students: 16% (6)	Students: 50% (12)	Students: 22% (2)
		Period 6: 30% Period 7: 30%	Postdocs: 100% (1)	Postdocs: 33% (2)	Postdocs: 20% (2)	Postdocs: 40% (4)	Postdocs: 13% (1)	Postdocs: 18% (2)
	Center’s alumni pursuing research in academia &	Period 6 -10: 30%	(new for P6-10)				Students: 38% (9)	Students: 78% (7)

	research labs in disciplines related to the Center						Postdocs: 88% (7)	Postdocs: 82% (9)
Center Management	Annual Surveys:	According to Likert Scale:						
	• Students /Postdocs	Period 2: 3 or higher	Average : 3.9±0.2	Average: 4.0±0.3	Average: 4.2±0.2	Average: 4.5±0.2	Average 4.3±0.2	Average 4.3±0.3
	• Co-PIs	Period 3: 3 or higher Period 4: 3 or higher Period 5: 3 or higher Period 6 - 10: 4 or higher	No survey in Period 2	Leader-ship: 4.46 Collaboration 3.25	Leader-ship: 4.7±0.5 Collaboration n/a	Leader-ship: 4.9±0.1 Collaboration Outside Theme: 1.3+/-0.1 Within Theme: 3+/-1	Leadership 4.6±0.1	Leadership 4.8±0.2
	• External Advisory Board		Strategic Plan: 4.18 Center Status: 4.01	Strategic Plan: 4.07 Center Status: 3.96	Strategic Plan: 4.6 Center Status: 4.6	Strategic Plan: 4.4 Center Status: 4.7	Center Legacy: 4.8±0.4	Center Legacy: 4.8±0.4
	Authorship disputes	Period 2: 20% decrease	0	0	0	0	0	0
		Period 3: 20% decrease		Faculty Ethics Survey: 4.39	Ethics Survey: no longer on Likert scale			
		Period 4: 20% decrease						
		Period 5: 20% decrease						
		Period 6 - 10: 0						
	Plagiarism	All Periods: 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

Research Accomplishments in Period 7

The Center brought together faculty researchers (co-PIs) 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 7, the Center's co-PIs have been:

- *Berkeley*: Jeffrey Bokor, Constance Chang-Hasnain, Felix Fischer, Ali Javey, Tsu-Jae King Liu, Steven Louie, Sayeef Salahuddin, Vladimir Stojanović, Junqiao Wu, Ming C. Wu, and Eli Yablonovitch
- *MIT*: Dimitri Antoniadis, Vladimir Bulović, Jesus del Alamo, Eugene Fitzgerald, Jing Kong, Jeffrey Lang, and Timothy Swager
- *Stanford*: H.-S. Philip Wong
- *UTEP*: David Zubia
- *FIU*: Sakhrat Khizroev

Steven Louie (Berkeley) and Jing Kong (MIT) joined the Center at the end of Period 6 and started research efforts at the beginning of Period 7. Both researchers are part of the nanoelectronics theme.

Theme I: Nanoelectronics – Key Accomplishments:

- *III-V Nanowire TFETs:* The **Yablonovitch** group (*Berkeley*) and the **Antoniadis** and **del Alamo** groups (both at *MIT*) have continued to perform detailed studies of trap-assisted tunneling at both the simulations/modeling and the experimental level. The model system used in these studies are vertical III-V nanowire TFET structures fabricated at *MIT* [6]. The **del Alamo** group has made excellent progress in improving the verticality of the bottom-up fabricated InGaAs nanowires, enabled by refinement of the III-V reactive ion etching (RIE) technology. The improved verticality of the nanowire sidewalls and the uniformity of its diameter has resulted in a significant mitigation of the strong asymmetry that was observed in the subthreshold characteristics in earlier generations of transistors. With the new, more symmetric devices, the large change in the saturated subthreshold swing (S_{sat}) and the drain-induced barrier lowering (DIBL) when the source and drain are swapped (BES: source at bottom; TES: source at top) is strongly improved. In addition, the **del Alamo** group has developed a new alcohol-based digital etch scheme that enables trimming of the InGaAs nanowires down to below 10 nm. This is the target range for the E^3S nanoelectronics program since modeling in the Yablonovitch group has revealed that InGaAs vertical nanowires TFETs with with sub-10 nm nanowire dimensions can support a single 1D subband. With further improvements of the RIE chemistry, etching InGaAs- and InGaSb-based heterostructures is possible at a similar rate with high aspect ratio and smooth sidewalls were obtained. This new etching technique will be key for the future fabrication of InAs/GaSb vertical nanowire TFETs.

A true Center team effort with participation of the **Antoniadis** and **Yablonovitch** groups, former E^3S student **James Teherani** (now assistant professor at Columbia University) and our industrial partner **IBM** has led to the discovery of a new parasitic leakage current that was previously unrecognized in TFETs: Auger generation (a process identical to impact ionization, and it is also the inverse process of Auger recombination) [15]. The team found that this is an intrinsic mechanism and is key to explain the discrepancy between TFET experiments and simulations. This work exposed the intrinsic link between the Auger and band-to-band tunneling rates, highlighting the difficulty of increasing one without the other. In fact, the team showed that Auger generation, contrary to the extrinsic trap-assisted-tunneling, imposes a fundamental limit on ultimate TFET performance.

- *Layered Chalcogenide TFETs:* 2D Transition metal dichalcogenides (TMDCs) such as MoS_2 and WS_2 are particular attractive semiconductor candidates due to their high potential for structural perfection. Using quantitative photoluminescence (PL) spectroscopy as a metric to measure material quality the **Javey** (*Berkeley*) group has developed an air-stable, chemical surface defect passivation scheme (an organic superacid) for exfoliated 2D MoS_2 that resulted in an internal quantum yield efficiency approaching 100% [8]. In a collaborative effort with the **Kong** (*MIT*) group, this defect passivation method was successfully applied also to CVD-grown 2D MoS_2. Once released from the growth substrate, the super-acid treatment increased the internal quantum efficiency of CVD-grown MoS_2 by more than two orders of magnitude. The **Javey** group successfully applied the super-acid treatment method also to other 2D-TMDC, including WS_2. Photoluminescence studies were used to fully characterize and understand edge-recombination in 2D WS_2, and crucial parameters such as exciton diffusion length and non-radiative edge recombination lifetime were determined. Results of these characterization studies will guide development of high-performance devices.

- *Graphene Nanoribbon Quantum Tunneling Structures:* The experimental aspects of the graphene nanoribbon (GNR) project have continued to be led by the **Fischer** group (*Berkeley*) with broad theory support by the **Yablonovitch** group and the **Louie** group (*Berkeley*). The **Louie** group joined the Center for E^3S at the beginning of this period and brings extensive expertise in ab initio calculations of electronic structures into the nanoelectronics theme. Using model Hamiltonian methods and first-principles calculations, a model structure was developed and energy band structures were calculated for a fully integrated system composed of different GNR structures that function as metallic leads, a barrier section, and a central quantum dot (QD) structure. Distinctive electronic properties were discovered, including near metallic character of a zig-zag GNRs, tunable band gaps in boron doped GNRs, and well separated energy levels within the QD region. Using this theory guidance, the **Fischer** group has continued to develop bottom-up synthesis and assembly strategies for heterostructure GNRs. In Period 7, particular emphasis has been directed towards integrating molecularly defined QDs that are flanked by two atomically defined tunneling barriers into a semiconducting GNR. Molecular precursors for QDs were derived from porphyrins that are structurally compatible with a series of molecular precursors for GNRs. The unique molecular structure and highly tunable electronics of porphyrin-derived QDs enables to rationally fine-tune the structural and electronic properties between the semiconducting GNR and the inserted QD, which are monitored by various scanning probe microscopies. Recently, computational methods have been applied in collaboration with the **Salahuddin** group (*Berkeley*) to analyze the performance of the fabricated device architectures. These calculations are the basis for discussions with the **Yablonovitch** group toward rationally guiding the design of improved generations of bottom-up fabricated QD tunneling junctions.

Theme II: Nanomechanics – Key Accomplishments:

- *Ultra-Low-Voltage Relays:* The **King Liu** group (*Berkeley*) minimized hysteresis voltage of electro-mechanical switches (relays) through a new, non-pull-in-mode device design [16]. With body biasing, very low voltage operation has been demonstrated. In fact, 100 mV operation of an inverter circuit comprising a body-biased relay functioning as a pull-down switch and a resistive load was successfully demonstrated. The **King Liu** group also designed vertically oriented relays to be fabricated using a standard 65 nm CMOS process, using the back-end-of-line (BEOL) interconnect (metal) layers. Specifically, body-biased logic relays and single-pole-double-throw (SPDT) relays for non-volatile memory were designed and simulated. The designed relays will be fabricated by IBM and the devices will be released at UC Berkeley using dry and wet etching. On the system level, the **Stojanovic** group (*Berkeley*) has continued its collaboration with the **King Liu** group and analyzed the application of NEMory relays in creating dense, low-energy nonvolatile memory (NVM) arrays with pattern-matching capabilities. Efforts are also underway to evaluate the energy/area/timing analysis of non-volatile reconfigurable logic based on NEMory devices.

  The **J. Wu** and **King Liu** groups (both *Berkeley*) developed an alternative approach for lowering the contact adhesion energy by using an anti-stiction molecular coating. For this, a vapor-phase molecular coating process developed by the **Squitch** group at *MIT* was applied at *Berkeley* to coated relays with a molecular self-assembled monolayer (SAM). Using this approach, the hysteresis voltage was significantly reduced. A current disadvantage of this approach is that in SAM coated devices, the transitions between OFF and ON states are less abrupt, i.e. the subthreshold swing is increased; however, if a smaller ON/OFF current ratio (e.g. 10^4) is sufficient, then the coated relay can be operated with a smaller gate voltage swing. It should be noted that by applying a body bias to bring the molecular coatings on the opposing conducting electrodes into contact, a metal-molecule-metal "squitch" structure is effectively achieved. This project thus uniquely incorporates the "squitch" idea [9] into a conventional electrostatic relay design.

- *Squitch: Molecular Squeeze-Switch:* In the current period, the research groups of **Vladimir Bulovic**, **Jeffrey Lang** and **Tim Swager** (all *MIT*), the **Squitch** group, has significantly improved the growth process and uniformity of the nanoplates (serving as gap electrodes) to facilitate reproducible assembly of nanogaps. For the assembly process growth of a hydrophobic alkanethiol layer to functionalize the nanoplate surfaces was introduced. The directed assembly was also improved by optimizing the surface properties of the substrate used in assembly, the assembly temperature, and the ratio of the two immiscible solvents used. During the assembly process, the nanoplates are suspended at the interface between two immiscible solvents. They are chemically treated, causing them to descend as the solvents dry into a closely-packed single layer on a glass substrate while maintaining a 20-nm or so lateral separation, after which gold interconnects and contact pads are deposited over their edges securing them in place. To compensate for the non-uniform thickness of nanoplates, which would result in an unacceptable step in height across the gap, the **Squitch** group developed a new post-assembly processing technique, which takes advantage of the fact that the bottom surfaces of the nanoplates against their substrate are co-planar. Therefore, after drying, the nanoplates are coated with an epoxy-like binding layer to hold them in place, and peeled as a continuous layer off the original substrate. This reveals an organized planar array of closely-spaced gold electrodes that are electrically isolated and atomically smooth. Moreover, this process can also be extended to fabricate three-terminal squitches with a recessed gate to prevent gate tunneling currents by using a sacrificial layer beneath the nanoplate that becomes the gate electrode. During the past year the **Squitch** group developed this fabrication process extension, and demonstrated the ability to recess the gate electrode by at least 4 nm as shown in the surface topography scan. This is sufficient to prevent gate tunneling.

Process was also made in the final two fabrication processes: (1) growth of the molecular monolayer that fills the squitch gaps and supports the moveable electrodes, and (2) placement of gold nanocubes on top of the nanoplate gap so as to straddle boundaries between nano-plates. The first process was accomplished using thiol chemistry to attach alkane or polyethylene glycol to the gold electrodes, and confirmed by nanoscale IR spectroscopy. The placement of gold nanocubes across the nanoplate electrode gap was achieved through a process that resembles dielectrophoresis. To prevent that many cubes straddle one gap, the **Squitch** group placed a large resistance in series with each gap. The first cube attracted then shorts the gap and thereby stops the local dielectrophoresis process. This process enabled the fabrication of an array of single-cube squitches. For a two-terminal squitch fabricated by this process, the tunneling currents were measured. It was found that the repeatability of the conduction cycles has been substantially improved.

- *Stritch: 2D Chalcogenide Stretch-Switch:* The **Zubia** group (*UTEP*) has been collaborating with the **King Liu** and **Javey** groups (*Berkeley*) in the design, fabrication, and testing of stritch devices (a stretch-switch operating by stretching a 2D transition metal dichalcogenide, TMDC, layer using a MEMS actuator, and thereby changing its bandgap and conductivity). A key outcome in this period has been experimental proof-of-concept of the stritch device. Another key accomplishment was the modeling of the device which incorporates mechanical and electronic aspects. Stritch devices with 2 and 3 monolayers of MoS_2 were also fabricated and tested. Simulation using only the width of the TMDC as a fitting parameter showed good agreement with experimental results. Modeling predicts that a stritch with a steepness of 13 mV/dec while maintaining an ON/OFF ratio of 10^6 can be achieved with a TMDC width of 8.5 nm. The Zubia group also conceptualized and modeled a stritch-based inverter. Since electrostatic force is ambipolar, the device can be used to implement inverting and non-inverting digital and analog circuitry.

Theme III: Nanophotonics – Key Accomplishments:

- *Antenna-Enhanced III-V nanoLEDs:* In Period 7, this collaborative project between **Ming Wu** and **Eli Yablonovitch** (both *Berkeley*) and **Eugene Fitzgerald** (*MIT*) has reached a milestone by demonstrating a >100-times spontaneous emission enhancement in electrically-injected III-V nanoLEDs. This milestone was achieved through optimization of antenna design, process improvements, and device scaling. Furthermore, design and growth of epitaxial wafer material with significantly improved quantum efficiency was achieved. Interestingly, a detailed analysis of our antenna LED design indicates that the requirements for edge passivation of the III-V antenna-LED can be lessened, much as they are for ridge lasers in which stimulated emission competes successfully against non-radiative edge recombination. In the case of the antenna-LED, the accelerated spontaneous emission can compete successfully against III-V edge recombination. This surprising result raises possibility of making a practical antenna-LED using conventional III-V materials and processing methods. This suggests that the antenna-LED might take its place among other important opto-electronic components needed for optical communications, sooner than would be the case if exotic new materials and processes would need to be developed.

  A new InGaAs/InGaAsP LED structure was designed by the **M. Wu** group and grown by the **Fitzgerald** group using MOCVD process. A test LED built from the new wafer has 10x higher peak quantum efficiency compared with previously employed purchased wafers. Furthermore, the new wafer reaches peak quantum efficiency at a significantly smaller current density suggesting that current injection efficiency is greatly improved compared with previous wafers. Preliminary measurement of a nanoLED coupled to optical antenna using this new epitaxial material shows higher brightness with respect to previously fabricated antenna-LED's, which is an outstanding materials contribution by the **Fitzgerald** team.

Members of the nanophotonics theme have also completed analysis of predicted direct modulation speed and spontaneous emission enhancement of optimized III-V antenna-LED. It was found that >100 GHz direction modulation speed is possible with > 25% quantum efficiency by using a multiple quantum well (MQW) active region that is heavily doped p-type. At the same time, it is expected that >300 photons can be emitted per clock period, which is more than enough for projected photo-receiver sensitivity at the system level.

- *Chalcogenide Antenna-LEDs:* An alternative photo-transmitter material is represented by the new monolayer chalcogenide semiconductors, which are being explored for the possibility of diminished non-radiative edge recombination compared to the III-V materials. This project is a collaboration with the **Javey** group (*Berkeley*), taking advantage of their extensive expertise in 2D monolayer chalgcogenide materials. It should be emphasized that this inter-disciplinary collaboration is a hallmark of the Center for E^3S. In the current period, the chalcogenide nanoLED concept was extended to all-important electrical injection, and a functioning device has been simulated and demonstrated by the **Wu** group on a dual back gates device to form a PIN junction. Improvements were also made to the measurement setup in collaboration with the **Yablonovitch** group. The improvements now allow for the measurement of scattering properties and photoluminescence emission from individual antennas. This greatly improves the ability to characterize devices and probe the different mechanisms for enhanced light emission. In particular, this setup now allows to distinguish from enhanced pumping and enhanced emission of our WSe_2 monolayers. Scattering measurements also enable to characterize antennas without the presence of an active material which greatly speeds up device prototyping.

  In a new development, by applying an AC voltage (kHz to MHz frequencies) to a back gated device, bright electroluminescence can be observed near the contact. The highest efficiency achieved for these devices is estimated at $\sim 10^{-6}$, compared to $\sim 10^{-9}$ for PIN diode devices. Capacitive coupling might provide a simpler fabrication route for testing optical antennas, and might actually be practical for a real optical communications link.

- *First Principles Analysis of the Photo-Receiver as a Systems/Physics Problem:* From the beginning of the Center, the nanophotonics theme has recognized that a highly sensitive photo-receiver with a low capacitance as a key to reducing the energy consumption of the complete optical link. The reason is that low detector capacitance reduces both the photons/bit required from the transmitter side as well as providing larger receiver signal voltage, reducing amplifier energy consumption. Owing to the highly integrated nature of the Center for E^3S, with device researchers being guided by circuits and systems researchers, we have done a complete re-examination of the detector/pre-amplifier/bit comparator photo-receiver system (details are given in the Research sections of this Annual Report). We have presented this parallel solution to the silicon photonics industry, and they seem poised to adopt this innovation, which would greatly improve their throughput and reduce their energy consumption. If this happens, then we will be able to regard this as an important success of the Center for E^3S.

  In agreement with previous studies, E^3S nanophotonics researchers have found that the photodetector be of sufficient size to absorb the photons, while the nanoscopic, short-transit-time, high-speed amplifier pre-amplifier must be small, presenting mutually conflicting requirements. Thus the photo-transistor effort in the Center, which tried to combine both functions in a single device, has been eliminated. Nonetheless the detector and amplifier functions must be as tightly integrated as possible, to reduce the capacitance of the interconnect wire. At present, this strategy is not being pursued by the silicon photonics industry, since it would require new engineering costs associated with necessary process changes. For the goals of the Center for E^3S, this approach will be essential in the future, since the antenna-LED is a nanoscopic device with a very small active region that is limited in the number of photons/bit that can be produced. Sensitivity, low noise, and high-speed are essential in the photo-receiver. Along these lines, we believe that it is time to provide optical cavity-enhancement to the photo-diode function.

Theme IV: Nanomagnetics – Key Accomplishments:

- *Picosecond Magnetic Switching:* In the current reporting period, the **Bokor** group in collaboration with the **Salahuddin** group (both *Berkeley*) demonstrated fast magnetic switching of the ferrimagnet GdFeCo when hit with laser pulses as long as 10 ps—as opposed to femtosecond excitation in previous work [14]. Following this promising result for potential electrical pulse induced magnetic switching, ways to generate picosecond electrical pulses were explored. Making use of an ultrafast photoconducting switch (sometimes referred to as an "Auston switch") they were able to launch 2-5 ps electrical current pulses on a microwave stripline. When this pulse was injected into a GdFeCo resistive load, indeed, ultrafast magnetic switching of the ferrimagnet GdFeCo was observed, as detected by time-resolved MOKE microscopy. This is a completely new mechanism of magnetic switching and opens the door to on-chip operation using conventional CMOS electrical pulses. To pursue this goal, a new collaboration has been initiated between the **Bokor** group and the group of **Philip Wong** (*Stanford*). This collaboration brings in the **Wong** group's expertise in integrating novel devices on top of CMOS and it would not have been possible without the Center because the two groups would not have become aware of each other's work and expertise otherwise.

  In addition, the **Bokor** and **Salahuddin** groups are exploring ways to extend ultrafast switching observed in ferrimagnetic GdFeCo to ferromagnetic materials. A promising step in this direction has been the observation of ultrafast, helicity independent, optical single-shot toggle switching of a thin CoPt ferromagnetic layer grown on a GdFeCo layer. When this stack is irradiated by single 55 fs laser pulses, reliable toggle switching of the two coupled layers is observed. The ability to switch a ferromagnet by ultrafast excitation will greatly expands options for design of an integrated switching and readout device.

- *Spin-Orbit Torque Switching and Magnetic Tunneling Junction Devices:* The **Salahuddin** group has studied spin-orbit torque (SOT) switching of ferrimagnetic $Gd_x(Fe_{90}Co_{10})_{100-x}$ films, denoted as GFC, for both transition metal (TM)-rich and rare earth (RE)-rich configurations. Systematic experiments were performed with a large number of samples having different volume fraction of Gd. All samples were fabricated using ultra-high vacuum sputtering and characterized by conventional magnetometry such as the vibrating sample method (VSM). The group observed that the value of the saturation magnetization drops around the compensation point for the magnetic moment. It is interesting to note that the torque efficiency peaks right around the compensation point. While this is currently not well understood, the torque efficiency going up around the compensation point might indicate a non-trivial effect on the spin angular momentum of the two sub lattices since the torque is exerted through angular momentum transfer. Currently, theoretical work is underway to predict and explain this observation.

  The **Khizroev** group (*FIU*) has made further progress in understanding and utilizing the new physics of spin-transfer torque (STT) magnetic tunneling junctions (MTJs) in the previously unexplored sub-10-nm size range. The experimental approach pursued by the **Khizroev** group uses a nanoparticle-based device structure. The nanoparticles are made of the high-anisotropy ferrimagnetic material $CoFe_2O_4$ while the magnetic layers are made of traditional high-anisotropy CoFeB compositions used in STT junctions. The nanoparticles are separated from the two magnetic layers by a thin layer of MgO (~0.3 nm). The measured I-V curves confirmed the single-electron behavior of such junctions; a characteristic Coulomb stair could be observed. The room-temperature magneto-resistance curves show sharp peaks with a magnetoresistance value above 100%. This is a significant result which shows that indeed the spin physics in such small nanoparticles could be used to significantly increase the magnetoresistance value in next-generation spintronic devices. Moreover, the Khizroev group's theoretical predictions (using a trivial model of field-dependent Landau energy levels) for the room-temperature MR value are above 10^5—provided that nanoparticle size can be further reduced.

- *Computing using Magnetic Nonvolatile Devices:* This project started in the previous period by the **Stojanovic** (*Berkeley*) and **Bokor** groups but has significantly expanded in this period by the **Wong** group joining the team. The **Stojanovic** group analyzed the mLogic circuit and also the more general transpinor-based logic efficiency and optimization. Furthermore, new ways to improve the energy at the circuit level were investigated, such as capacitively-coupled spin-logic (CC spin-switch) and hybrid spin-CMOS logic for nonvolatile D flip-flop and SRAM cells were investigated. Experimental efforts for integrating spin Hall devices with FETs to build SRAM and flip-flops, and to show that the circuits are nonvolatile and have no impact on circuit area, were led by the **Wong** group. Significant progress has been made in the fabrication of the example circuit and the fabrication of the spin switches. The final step will be integration of the two. The nonvolatile latch circuit the group is building is a CMOS latch with an input, a clock, and outputs Q and Q_B. Two spin switches with oppositely magnetized wires are attached to the latch. The "store transistor" stores Q into the magnetization of the spin switch, and the "load transistors" reloads Q into the circuit.

  The first key outcome in this period was completion of a tapeout of the latch using 130 nm CMOS. The second key outcome was full fabrication of the spin switch in collaboration of the **Wong** and **Salahuddin** groups. It consists of a magnetic wire with a tunnel junction in the center. The team chose to switch the memory devices using the spin Hall effect, which is about 100x more energy efficient than more traditional spin torque transfer. Thus, thin film stacks were grown by sputter deposition and UHV annealing and optimized to have perpendicular magnetic anisotropy, which is also desirable for more energy-efficient switching. The magnetic wire could be switched using the spin Hall effect down to 150 nm wide wires, within the design parameters of circuit. It should be emphasized that about 10-times lower switching current density were measured than with spin transfer torque switching. Finally, the **Wong** and **Salahuddin** groups developed and carried out full fabrication of the device with the tunnel junction in the center of the wire. The process uses electron-beam lithography and includes five lithography steps and three etch steps using tools at *Stanford* and *Berkeley*. The group started a collaboration with the Center's industrial research partner Applied Materials to use their highly optimized thin film growth. Samples from Applied Materials displayed TMR = 285%, one of the highest TMR reported. The switching of the free magnetic layer occurs around 5 Oe and the fixed layer switches around 1500 Oe. This collaboration with one of the Center's industrial research partners is an excellent example of the importance of having a Center structure.

Education and Diversity Accomplishments in Period 7

Since the start of the Center, E[3]S Director, **Eli Yablonovitch** (*Berkeley*) has been biennially teaching a graduate level course on low energy electronics with a strong focus on E[3]S topics and perspectives. In Period 7, the UC Berkeley listed course, was taken by 7 graduate students and 2 postdocs from within the Center. In addition, curriculum has been implemented into courses taught by E[3]S faculty that focuses on low energy electronics, the Center's approaches, and some of the research outcomes.

The Center also offers a variety of practical training opportunities for graduate students and postdocs, including both oral and poster presentations, presenting at seminars and during Center events, mentoring of undergraduates, group analysis of competing research, participating in the REU intern selection process, serving as poster judges, and conducting scientific demonstrations at outreach events. Given the number of opportunities available, the Center has developed the E^{3}S Professional Development Program (E^{3}S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences. Upon completing four development areas, a student/postdoc will receive a Leadership Certificate. Thus far, 17 students have earned a certificate of completion.

Intended to be pathway programs, the E^{3}S and TTE REU Programs, are designed to continue engagement after the internships end. Post program engagement comes in three ways: 1) a travel award to present the research outcomes of the internship at a conference; 2) advice and support through the application process for either transfer admissions to a four-year institution and/or graduate school; and 3) annual surveys to track the progress of the program alumni. In Period 7, one REU alumni presented his research at the 2016 Frontiers in Optics annual meeting. Two TTE alumni gave poster presentations at the 2016 SACNAS annual conference, and one gave a poster presentation at the 2016 CUR REU Symposium.

The Center has a strong record of REU program alumni going on to transfer and further their careers in graduate education. To date, 69% of undergraduate REU alumni have enrolled in a graduate program in science or engineering and 80% of community college students who did research with E^{3}S or E^{3}S affiliated faculty last year have transferred to Berkeley.

Knowledge Transfer Accomplishments in Period 7

Knowledge transfer through the dissemination of results and outcomes from research, education, and diversity activities has received broad support by all members of the Center—as has been the case in previous years—and has remained the key knowledge transfer avenue of the Center for E^{3}S. 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 the Center has informed the peers, and the general public about key activities, results and accomplishments.

Since the Center for E^{3}S considers knowledge transfer a two-way road, it actively solicited information and results from various sources external to the Center. This is done, for example, by regular contacts (seminars, visits, workshops) with the Center's Industrial Research Board composed of companies that the Center considers to be key players and the areas of research most closely related to the Center. Furthermore, the Center is also active in transferring knowledge gained from the Center's research and education activities in the areas of low-energy electronics to other applications. For example, Squitch Switches as Analog Valves and RIE process with Digital Etch Technology for III-V Features of High Aspect Ratios have been pursued with various companies.

In this period, the Center has initiated and co-organized a new workshop with the goal to increase diversity in student education: The Berkeley HBCU Workshop was held in March 2016 in partnership with the UCB-HBCU summer REU program (**Tsu-Jae King Liu**, PI) (*Berkeley*), which is funded by the University of California Office of the President and is managed and operated by E^{3}S staff as part of our summer REU portfolio. The workshop attendees included representatives of all four HBCU schools that participated in the 2016 UCB-HBCU program. An expanded version of this workshop in spring 2017 is in the planning stages.

Finally, an important knowledge transfer activity has been the biennial Berkeley Symposia for Energy Efficient Electronic Systems organized by the Center in odd-numbered years. We are currently in the planning stages for the 2017 Berkeley Symposium, which will be held in October, and for the first time, will be a joint meeting with the Steep Transistor Workshop. In addition, we have plans to partner up with the IEEE S3S Conference and become a satellite event.

Center Management Changes in Period 7

The Center's leadership and management team underwent some changes in Period 7. Most notably, **Kedrick Perry** (*Berkeley*) replaced **Aimee Tabor** (who unexpectedly passed away in December of last year) as Diversity and Outreach Director, and **Aine Minihane** (*Berkeley*) replaced **Fanny Li** in the role of Program Coordinator. A change occurred also in the E^3S Executive Committee, which welcomed the Diversity and Outreach Director, **Kedrick Perry**, and the Education Manager, **Lea Marlor** (*Berkeley*), as observers.

The Center for E^3S External Advisory Board experienced several changes in Period 7. In 2016, two external advisors, **Mark Pinto** (*Blue Danube Labs*) and **Peter Delfyette** (*University of Central Florida*) completed their 3 year terms. Both were thanked for their excellent service to the Center and were excused from the External Advisory Board. The Executive Committee approached **Thomas Theis** (*Columbia University*) to join the External Advisory Board. Prof. Theis, who just moved to Columbia University as new executive director of the Columbia Nano Initiative, agreed to serve on the External Advisory Board but asked to delay his start date to March 2017.

Center Output in Period 7: Table 1.2.

Publications	
Peer Reviewed Journal Publications	29
Submitted for Review	10
Peer Reviewed Conference Proceedings	12
Books and Books Chapters	0
Conference Presentations	50
Other Dissemination Activities	36
Awards and Honors	14
Ph.D. and M.S. Graduates	4
Postdoc Alumni	11
Patents and Patent Disclosures	5

Summary of Plans for Period 8

Research Plans for Period 8

The research efforts in Period 8 will be guided by the Strategic Research Plan (given above), and no major changes in the research directions of the four themes and system integration are planned in the upcoming period. The only change in faculty participation will be that **Dimitri Antoniadis** (*MIT*) will phase out of the Center within the first few months of Period 8. This decision was made between Prof. **Antoniadis** and the Center leadership as a result of the emphasis of the nanoelectronics research focus from traditional III-V semiconductors to new types of semiconductors, such as two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs). This transition in research strategy in the nanoelectronics theme has been in progress during the last two periods and came to full fruition in this funding period with the addition of Profs. **Jing Kong** (*MIT*) and **Steven Louie** (*Berkeley*).

Theme I – Nanoelectronics: The nanoelectronics research efforts will be led by **Eli Yablonovitch** (*Berkeley*) and will investigate band-to-band tunneling at low turn-on voltage in traditional semiconductors as well as exploring tunnel devices based on new two-dimensional semiconductors. Research on traditional semiconductors will be aimed at understanding of the role of interfacial traps as detractors to band-to-band tunneling, and will be conducted mainly in the **del Alamo** group (*MIT*) and the **Yablonovitch** group. Research toward new low-defect density semiconductors will continue to focus on (1) optimization of transition metal dichalcogenide TFETs by the **Javey** (*Berkeley*) and **Yablonovitch** groups and the **Kong** group (*MIT*), and (2) bottom-up synthesis, assembly and characterization of graphene nanoribbon based tunneling devices. The latter efforts will be led by the **Fischer** group (*Berkeley*) in collaboration with the **Swager** group (*MIT*), and will be guided by theoretical studies by the **Louie** (*Berkeley*) and **Yablonovitch** groups.

- *III-V Nanowire TFETs:* The goal of **del Alamo** group is to fabricate ~10 nm diameter VNW MOSFETs, TFETs and superlattice-source FETs. In collaboration with the **Yablonovitch** group, the **del Alamo** group will also develop a 3D simulation environment that solves electrostatics and quantum confinement effects self-consistently to help explain experimental characteristics of nanowire TFETs and MOSFETs and design new device structures.
- *Chalcogenide TFETs:* The **Javey** and **Kong** group will continue to extend the superacid treatment to heal defects of CVD and MOCVD grown TMDCs and subsequently demonstrate high performance 2D-2D tunneling field effect transistors. Characterization results will be analyzed in collaboration with the **Yablonovitch** group with respect to bandgap defect state densities, D_{it}.
- *Graphene Nanoribbon TFETs:* Guided by first-principles calculations results by the **Louie** group the **Fischer** group will design and synthesize molecular building blocks featuring metallic band structures as well as quantum dot heterostructures. Assembly of this segmented GNR heterostructure both on surface as well as in solution will be done in collaboration with the **Swager** group.

Theme II – Nanomechanics: The nanomechanics research efforts will be led by **Tsu-Jae King Liu** (*Berkeley*) and will focus on the theme's goal of demonstrating reliable nano-electromechanical (NEM) switch (or relay) operation at or below 10 mV. The three main research topics of Period 7 will also continue in Period 8: 1) Design and fabrication of body-biased NEM relays led by the **King Liu** group in collaboration with the **J. Wu** and the **Stojanovic** groups (both *Berkeley*). 2) Reproducible fabrication of Squitch devices with reduced operating voltage by the *MIT* **Squitch** team of the **Lang**, **Bulovic,** and **Swager** groups. 3) Optimization of the Stritch device design and characterization of switching properties led by the **Zubia** group (*UTEP*) in collaboration with the **King Liu** and **Javey** groups (both *Berkeley*).

- *Low-Voltage Relay Design:* Work in the **King Liu** and **J. Wu** groups will be devoted to optimize the molecular material to achieve steeper effective subthreshold swing without increasing the contact adhesive force and thus, to enable operation with even lower voltage swing. In addition, the performance and reliability of relays with molecular coatings will also be systematically characterized in collaboration with the **Louie** (*Berkeley*) theory group.
- *Squitch Project:* The Squitch team comprised of the **Bulovic**, **Lang,** and **Swager** groups plan to transition from fabrication process development to device development through optimized design, fabrication, and testing. The primary development objective will be to lower the actuation voltage of the squitch. In addition, in collaboration with the **King Liu** group a plan is in place to transition to more extensive use and testing of three-terminal squitches over two-terminal squitches.
- *Stritch Project:* Project leader **David Zubia** will continue to work closely with the **King Liu**, **Javey**, and **J. Wu** groups and plans to use MEMS chevron actuators to match the size of the TMDC flakes to the electrode pads and improve control of strain. It is expected that these device developments will lower voltage operation, increase ON/OFF ratio, improve device reliability, and increase process yield.

Theme III – Nanophotonics: The nanophotonics research efforts will be led by **Ming Wu** (*Berkeley*) and will continue to focus on making progress toward on-chip few-photon optical communication between electronic switches at unprecedented efficiency levels. The goal remains to experimentally reach several orders of reduction of photons-per-bit in a data-link from the current 20,000 photons/bit level. This goal of the **M. Wu**, **Yablonovitch**, **Chang-Hasnain** (all *Berkeley*) and the **Fitzgerald** group (*MIT*) will be pursued by further improving the antennaLED (both the III-V and chalcogenide approaches) and analysis/optimization of the photoreceiver integration at the systems level (**Stojanovic**, **M. Wu**, **Yablonovitch** groups; all *Berkeley*).

- *Antenna-Enhanced III-V nanoLEDs:* The **M. Wu** and **Yablonovitch** groups plan to further improve the efficiency of electrically injected III-V antennaLEDs by redesigning part of the device structure. The **Chang-Hasnain** group will contribute toward this goal by developing a method for an ultrathin layer of InP over-growth on the nano-patch to reduce surface recombination. The **Fitzgerald** group will continue to work on epitaxial challenges related to fabrication of low-energy antenna-enhanced LEDs focusing on heavy p-type doping in the active region. In addition, growth optimization of InGaAsP/InGaAs multi-quantum well LED structures integrated with an InP waveguide structure will be pursued. This will be a first step towards demonstrating a full optical link including an LED, waveguide, and detector.
- *Chalcogenide Antenna-LEDs:* The **M. Wu**, **Yablonovitch** and **Javey** groups (all *Berkeley*) will focus on quantifying and improving emission rate enhancement from antenna-coupled devices in electoral injection mode. The chalcogenide antenna-LED group plans to demonstrate >100-fold antenna enhancement in an electrically injected TMDC device, understand the mechanism of electroluminescence in AC-gated devices, and perform time-resolved measurements of photoluminescence to determine recombination coefficients and the antenna's effect on exciton lifetime.

Theme IV – Nanomagnetics: The nanomagnetics research efforts will be led by **Jeffrey Bokor** (*Berkeley*) and will continue focusing on achieving an ultra-low energy magnetic switch operating at speeds of a few picoseconds. Electrical charge-induced picosecond magnetic switching will be further optimized by the **Bokor** and **Salahuddin** groups (both *Berkeley*) and in collaboration with the **Wong** group (*Stanford*), ultrafast magnetic switching using electrical pulses generated on-chip in CMOS circuits will be pursued. The underlying nature of spin torque transfer and nanometer-sized magnetic tunneling junction devices will be studied by the **Salahuddin** and **Khizroev** (*FIU*) groups, respectively, whereas the **Wong**, **Bokor** and **Stojanovic** (*Berkeley*) groups will continue to pursue computing using nonvolatile magnetic devices.

- *Picosecond Magnetic Switching:* The **Bokor** and **Salahuddin** groups will be to further investigate the details of the physics of electrical current switching and search for ways to reduce the peak current and total energy required for electrical switching. In collaboration with the **Wong** group, integrated CMOS and magnetic device circuits will be built to demonstrate ultrafast magnetic switching using electrical pulses generated on-chip in CMOS circuits.
- *Spin Hall Effect and Magnetic Tunneling Junction Devices:* The **Salahuddin** group will investigate the dependence of torque efficiency on thickness of the GdFeCo films to provide an understanding of the scaling of the torque, which, in turn, should provide critical insight into the physics of torque transfer. The **Khizroev** group will continue to exploit the new physics in magnetic tunneling junction devices with planar sizes in the sub-5-nm range in which surface effects dominate over volume effects. For this, both magnetic and magnetoelectric (ME) nanoparticles with a diameter ranging from 10 nm to below 1 nm will be synthesized, and with different shapes and symmetries, including spherical, rectangular, and pyramidal nanoparticles.
- *Computing using Magnetic Nonvolatile Devices:* The **Wong** and **Stojanovic** groups in collaboration with the **Bokor** group plan to achieve full integration of the CMOS and spin switches and testing of

the final circuit. The team also plans to conduct simulations and experimental realization of integration of the spin switches with 2D FETs to extend this project to not only using technologies that can be 3D monolithically integrated. Throughout, simulations and modeling will be used to quantify the benefits of normally-off computing.

Education and Diversity Plans for Period 8

In Period 8, the Center will have continuity in staffing with Education Manager, **Lea Marlor** (*Berkeley*), and Diversity and Outreach Director, **Kedrick Perry** (*Berkeley*), and the Center will remain committed to attracting diverse candidates to its education programs. The Education and Diversity efforts will continue receive faculty support from **Tsu-Jae King Liu** (*Berkeley*) and **Jeffrey Bokor** (*Berkeley*), in their roles as Associate Director of Education and Associate Director of Diversity, respectively. In addition, the Center's staff will seek the advice of the Education Working Group that is part of the E^3S External Advisory Board. The Education Working Group will meet in the Spring of Period 8 to discuss challenges and new opportunities for education and diversity growth.

Much of Period 8 will be spent continuing to strengthen internship programs with recruiting emphasis on attracting women, underrepresented minorities, first-generation students, veterans, and those of varying ability/disability status. For the REU program, we plan to utilize leveraged funding from the UC Office of the President to attract students from HBCUs. Through the activities of the UCB-HBCU program (PI: **Tsu-Jae King Liu**), as well as the development of institutional ties to HBCUs, the Center strives to build a legacy of engagement in energy efficient electronics science. **Kedrick Perry** will be continuing to work with the UCB-HBCU program and its faculty to recruit qualified applicants and build strong working relationships with faculty at the HBCUs as well as expand the number of HBCUs sending students to the REU. **Tsu-Jae King Liu** will work in conjunction with **Kedrick Perry** in the planning of a workshop to host HBCU faculty in Spring 2017 and further build upon these relationships.

By analyzing the data on REU alumni attending graduate school and joining the Center as graduate students, we recognized that interventions were still necessary. **Kedrick Perry** has led a review of the Center's diversity strategy and has identified new approaches to be adopted which include enhancing Center awareness, targeted recruitment, strengthening minority-serving institution partnerships, and building a culture of inclusive excellence. Implementation of these strategies began in Period 7 and will continue to frame recruitment efforts in Period 8. Moreover, the REU selection process for Summer 2017 will put greater emphasis in selecting electrical and electronics engineering undergraduates to ensure that when they successfully join one of the Center's member institutions, the program participants will be in a department with a choice of E^3S faculty to serve as their advisors.

For Education, emphasis will be placed on building the legacy of the Center through a combination of online education and training materials that relate to the research themes of the Center. Videos have already been created and more are in the pipeline. Development of publicity mechanisms to target audiences is ongoing. An action plan is being generated that will include the application of assessment tools to study the efficacy of the online teaching modules, particularly the collection of mini-course modules on Energy Efficient Electronics for new Center members. Also in development is an e-book which is geared towards a high school audience. By the beginning of Period 8, an outline of this book will be developed with content drafting to begin shortly afterward.

Knowledge Transfer Plans for Period 8

The Center will institute a new knowledge transfer avenue by the release of the Center for E^3S Blog Site, which will feature a continuous stream of blog entries from Center members including the Executive

Director, the Diversity and Outreach Director, the Education Manager, and a representative of the E^{3}S Student and Postdoc Council.

Another new transfer of knowledge activity will be the launch of a Center for E^{3}S site on the *nanoHUB.com* website platform. This platform will initially be used mainly for educational purposes and will include publication of an open-access e-book on energy efficient electronics. The e-book project is currently at an early stage of planning of the main chapters that will be included.

II. RESEARCH

1a. Goals and Objectives

The Center for E[3]S continues to combine a broad research and education approach to revolutionize two major fundamental components of digital information processing systems: the communications logic switch and the short-medium range communication of information between logic elements. The defining research goal of the Center for E[3]S has been guided by fundamental considerations and focuses on developing **systems operating at the minimum energy requirement for performing digital functions**. This ambitious goal is pursued by a collaborative approach, involving engineers, chemists, physicists, and materials scientists from five institutions (UC Berkeley, MIT, Stanford, UTEP, and FIU).

This grand challenge of reaching the minimum energy per bit is addressed by four research themes: Nanoelectronics (theme I), nanomechanics (theme II), nanophotonics (theme III), and nanomagnetics (theme IV). Overarching these four research themes is System Integration, leading to the common goal of new energy-efficient device architectures. Three of the main research themes focus on logic switching (nanoelectronics, nanomechanics, and nanomagnetics), while an optical approach is used for communication of information (nanophotonics). As a Science and Technology Center, part of the research goal is to understand on a fundamental level the strengths and limitations of each of the four approaches, and to elucidate for each approach the factors that determine the minimum energy requirements.

The foundations of the thermodynamics of computation were established by Landauer and Bennett; a good review of this work was published by Bennett in 1982 [16]. An oft-quoted result is that a computer operating at temperature T must dissipate at least $kT\ln(2)$ (about 18 meV at room temperature) per logical operation. This is frequently referred to as the "Landauer limit" [17]. However, for reversible, or adiabatic operations, in fact the minimum dissipation can even be made much less than kT [18]. For reference, leading edge CMOS today dissipates a minimum of ~400,000 kT (~10,000 eV) per digital function, when the energy required to charge the wires is included. The ITRS Roadmap [19] projects a goal for this value to be reduced to ~40000 kT (1,000 eV) per digital function in the year 2022.

While, in principle, digital logic systems can approach the Landauer limit [20], a new type of transistors is needed. Current state-of-the-art transistors lack the sensitivity to provide a good on/off current ratio (~10^6) at powering voltages below ~0.8 V. In fact, at the end of the CMOS roadmap, the operating voltage is projected to be ~0.7 V. Therefore, a new switch with the ability to operate at significantly lower powering voltage is needed. Figure 2.1 presents a schematic comparison of today's thermally activated conventional transistors with the desired properties of the new type of switches. Switch characteristics are parameterized by sub-threshold swing, S, where the 60 mV/decade is equivalent to the Boltzmann factor, and represents typical thermally activated devices. In this respect, it is important to distinguish between the energy requirement in eV units versus the voltage requirement in V units. A bit of information on a wire is represented by many electrons, easily satisfying the Landauer requirement >>kT, even when the voltage is <kT/q.

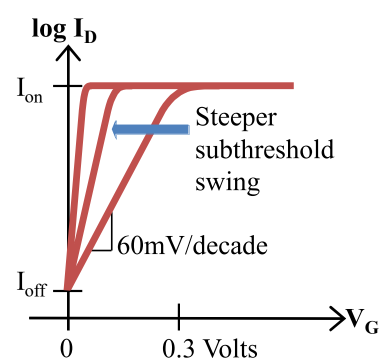


Figure 2.1. Current (logarithmic scale) vs. voltage V_G (linear scale) characteristics of a logic switch. In conventional transistors the subthreshold swing (S) is limited by the Boltzmann factor to a maximum steepness of $\ln(10)kT/q$ = 60 mV/decade at room temperature.

In its search for developing a new ultra-low energy switch, the Center for E[3]S recognized early on that this switch must meet a set of key specifications:

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

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

The third requirement of a milli-Siemens per μm conductance density (i.e. a 1 μm device should conduct at ~1 kΩ in the on-state) is critical for miniaturization and integration. For a small switch to deliver sufficient current to charge the wires in less than a clock period, the typical requirement for today's transistors 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 to these three key requirements, sub-threshold swing, on/off ratio, and conductance density that are directly applicable to the three themes addressing the communications digital switch, the nanophotonics theme is concerned with replacing current metal wires or interconnects with an optical solution. The ultimate goal of the nanophonotonics theme is to approach the quantum limit of 20 aJ/bit or 20 photons/bit as the lowest energy per bit interconnects.

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: 70% P9: 70% P10: 70%
	Multi-Institutional Projects	Yearly	P2: 10% P5: 30% P6: 15% P7: 20% P8: 25% P9: 25% P10: 25%
	Unplanned research projects *(discontinued in the 2nd five years)*	Yearly after Period 2	P3: 1 P4: 3 P5: 0
	New joint research funding opportunities *(replaced)*	Beginning in Period 3	P3: 1 P4: 2 P5: 2
	Publications with authors from multiple institutions	Yearly beginning in Period 2	P3: 12 P4: 2 P5: 4 P6: 5 P7: 5 P8: 5 P9: 5

			P10: 5
	New joint research funding awards *(new, as replacement)*	Yearly	P6: 1 P7: 0 P8: 1 P9: 1 P10: 1

Since all metrics and metric goals were reviewed and updated last year as part of the revision of the E^3S Strategic Plan, no further revision were undertaken this period. As was concluded last year, in the first five years, the Research metrics were set to measure: a) center synergy as in whether the Center members are forming and norming, in the lingo of group development; and b) performing as in whether new ideas that are generated from the interactions. However, after five years, the Center must be in the performing stage of group development and thus, we concluded that the research metrics should put more focus on the tangible results from the collaborations, as in joint publications and the new funding the Center's faculty jointly receive in support of expanding and sustaining the collaborations.

It should be emphasized that the continued struggle to meet the targets set with the metric "Publications with joint authors from multiple institutions", has led the Center leadership to institute a new multi-institutional postdoc program. This program gives each research theme an additional postdoc position. This position has to be filled with a postdoc, who will work jointly with faculty from at least two different E^3S institutions, and who will spend considerable time at these different institutions. Furthermore, it is the expectation of this new program that publications from the research project of the multi-institutional postdoc will have joint authorship from at least two different E^3S institutions.

1c. Problems Encountered

In Period 7, the Center for E^3S did not encounter any problems of the magnitude that would require major changes in research direction or at the personnel level. Instead, problems encountered in Period 7 have been typical of multi-institutional centers and research programs developing new materials, fabrication processes, device structures, metrology tools, and simulation methods. It should be emphasized that the Center as a whole made significant progress in its research goals across all four themes and system integration. The problems discussed below are mainly at the individual project level. Typical for a large Center, while each project is vital to the progress of a research thrust, the speed at which they proceed and the success rate can vary.

Theme I: The nanoelectronics theme has undergone a gradual transition in research direction during the last 2-3 years from device structures based on traditional III-V materials to new semiconductors based on two-dimensional materials. While the III-V vertical nanowire TFETs are important model devices for studying interfacial effects and trap-assisted tunneling mechanism on a fundamental level, inherent limitations in defect densities has led to a shift of resources and personnel toward the search for new material systems with ultra-low interfacial defect densities such as two-dimensional chalcogenides and graphene nanoribbons. A consequence of this programmatic transition is two groups leaving the Center (**Hoyt** in Period 6 and **Antoniadis** early in Period 8) and three new groups entering the Center (**Fischer** in Period 6, and **Kong** and **Louie** in Period 7).

- The **del Alamo** and **Antoniadis** groups (*MIT*) encountered problems with heterostructure growth in the fabrication of III-V TFET devices. In particular, issues arose with the Si doping level in InGaAs being too low, resulting in poor contact resistance which has hurt the On current of the devices. This yielded poor electrical results for transistors with nanowire diameters of 30 nm and below. The groups are currently working with the grower to address this problem of the calibration of Si doping level.

- Problems with passivation of edges in 2D chalcogenide monolayers have highlighted the importance of developing appropriate fabrication techniques of these new semiconductors. So far, the **Javey** group (*Berkeley*) has attempted to passivate edges during the fabrication process; however, this renders an unsatisfactory edge lifetime. Current efforts (jointly with the **Kong** group at *MIT*) to overcome this problem are focused on developing high-temperature CVD growth environments under the correct chemical environment.
- A challenge in the graphene nanoribbon (GNR) research has been to find metallic GNRs to serve as the lead in the transistor structure. The **Fischer** group (*Berkeley*) realized that previously envisioned zigzag GNRs are difficult to synthesize and air sensitive, hindering large-scale production for device applications. To assist the **Fischer** group in the rational design of metallic GNRs, the **Louie** group (*Berkeley*) has started first-principles calculations to explore doped GNRs with a wide range of dopant atoms and configurations.
- The **Fischer** group has also encountered unexpected problems during the co-deposition and self-assembly of heterostructures from GNR precursors and molecular quantum dots on surfaces. A redesign of the linker species is thus underway to mitigate this problem. The **Fischer** group has also expanded its synthetic strategies towards solution based polymerization techniques as an alternate route to GNR-quantum dot heterojunction architectures.

Theme II: Research efforts in the nanomechanics theme are multifaceted by inventing devices, materials and their fabrication processes all at the same time. Thus, challenges are primarily fabrication related and no significant problems were encountered other than the time it has taken to overcome challenges related to grow and integration of new materials.

- The **"Squitch"** group at *MIT* (**Bulovic**, **Lang**, **Swager**) had to modify synthesis methods to yield nanoplates and nanocubes with the desired size and size uniformity, and with the required smooth and flat surfaces to be useful in a squitch device. Current efforts focus on locating those materials in the orientation required for a squitch to function.
- With the recent acquisition and installation of an exfoliation/transfer station, a Raman/PL spectrometer, an e-beam depositor, and a profilometer, the **Zubia** group (*UTEP*) will be able to make progress in the theme's "Stritch" project by performing routine exfoliation and dry transfer of 2D chalcogenides onto MEMS. To compensate for the lack of e-beam lithography, dry etching, and suitable electrical characterization equipment at *UTEP*, the **Zubia** group will continue its student and postdoc visit program at *Berkeley*, working with the **Javey** and **King Liu** groups.
- In the last period the **King Liu** group has started to use molecular coatings of relay electrodes to counter stiction issues, and thus lower hysteresis voltage. The group found, however, relay operation with molecule-coated surfaces does not provide for lower voltage operation due to non-steep switching behavior. Currently, the **King Liu** group has joined forces with the **J. Wu** group (*Berkeley*) and the **Squitch** group work on overcoming this problem by "engineering" the molecular structure of the coating including the functional end groups and the spacer backbone.

Theme III: The nanophotonics theme has started a transition to phase out photo-receiver research with recent findings by the **Yablonovitch** and **Stojanovic** groups (*Berkeley*) that a systems level solution needs to be pursued. Some of the new features that will be needed to make a more sensitive photo-receiver are (1) cavity enhanced photo-diode, (2) a very large feedback resistor on the initial trans-impedance amplifier, compensated by high-pass frequency response in the succeeding amplifier stages and (3) multiple serial to parallel slicers that split the load on the parallel slow comparators that decide whether the bit is a 1 or a 0. While this new strategy might not be sufficient to reach the quantum limit, 20 photons/bit, it appears that two orders of magnitude improvement will be possible, relative to today's direct detection technology. For the up-coming Period 8, the theme led by Ming Wu thus has decided to focus on the photo-emitter efforts that have recently made significant progress with record-fast spontaneous emission from nanoLED devices. As a consequence, the **Chang-Hasnain** group (*Berkeley*) will shift its research focus and has proposed to develop ultrathin layer of InP over-growth on the patch area of electrically pumped InP/InGaAs nano-LEDs to reduce surface recombination—a recent problem due to the large surface/volume ratio and damages created by etching.

- The **Fitzgerald** group (*MIT*) has encountered problems of low current gains in GaAs(P)/InGaP HBT structures fabricated with heavy C base doping. The group found this was caused by a combination of low minority carrier lifetime in the base region and by high series resistance. By decreasing the C doping level of the base region and using Zn as a base dopant instead of C it was possible to increase current gains by an order of magnitude in fabricated devices.
- In the electrically-pumped nanoLED project, the **M. Wu** group (*Berkeley*) identified leakage from the gate dielectric a major problem. Since this may be caused by overetching the gate dielectric (h-BN) underneath the monolayer, the group now uses ALD to deposit the gate oxide instead of h-BN, which is selective to the etchant for the monolayer.

Theme IV: As announced in last year's report the nanomagnetics theme added the **Wong** research group (*Stanford*), which moved from theme II into theme IV. The **Wong** group will collaborate with the **Salahuddin**, **Bokor**, and **Stojanovic** groups (all *Berkeley*) on a new effort in-memory and normally-off computing using magnetic non-volatile devices. No major problems were reported in the nanomagnetics theme, which has made significant progress toward shedding light on the dynamics and mechanistics underpinnings associated with ultra-fast magnetic switching.

- The **Khizroev** group (*FIU*) encountered problems with focused ion beam (FIB) system at *FIU* as it was down for a considerate amount of time and exhibit resolution issues. This instrument is crucial for fabricating sub-5-nm spin devices needed for the current MTJ project of sandwiching nanoparticles between two magnetic layers. The Khizroev group took advantage of the collaborative nature of the Center for E^3S and send a graduate student to *Berkeley* for a 9-week summer stay to work with state-of-the-art FIB systems under the supervision of the **Bokor** group.

2a. Research Thrusts in Period 7

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 been guiding the research direction of the Center, and the following reporting of the research activities and progress should be viewed in the context of the Center's strategic research plan.

E^3S Researchers: The Center for E^3S has continued its collaborative research and education program, bringing together research groups from five academic institutions: UC Berkeley, MIT, Stanford, UTEP, and FIU. The faculty researchers (co-PIs) representing the research groups are:

- *UC Berkeley*: Jeffrey Bokor, Constance Chang-Hasnain, Felix Fischer, Ali Javey, Tsu-Jae King Liu, Steven Louie, Sayeef Salahuddin, Vladimir Stojanović, Junqiao Wu, Ming C. Wu, and Eli Yablonovitch.
- *MIT*: Dimitri Antoniadis, Vladimir Bulović, Jesus del Alamo, Eugene Fitzgerald, Jing Kong, Jeffrey Lang, and Timothy Swager
- *Stanford*: H.-S. Philip Wong
- *UTEP*: David Zubia
- *FIU*: Sahkrat Khizroev

As stated in last year's annual report, at the end of the last period, the Center added two new faculty researchers: **Jing Kong** (*MIT*) **Steven Louie** (*Berkeley*); biographies are given in Appendix A. Both Profs. **Kong** and **Louie** joined the nanoelectronics theme. It should be emphasized that both new faculty had an excellent start and significantly contributed to the Center progress and success in this period (details will be given further below in the research description section).

The participation of all 21 faculty researchers within the Center's main research themes is give in the table below. Note that **Vladimir Stojanovic** (*Berkeley*) leads the system integration efforts of the Center and collaborates with all four themes.

Table 2.2. Faculty Participation by Theme in Period 7

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

Legend: x* denotes Theme Leader

Center Synergy: The Center is structured into four research themes (nanoelectronics, nanomechanics, nanophotonics, nanomagnetics) and an overarching system integration thrust, consisting of a total of 18 projects. All of these projects address the Center's main goal of developing next-generation energy efficient electronics solutions. Faculty, postdocs, and students take advantage of the collaborative Center structure within E^{3}S, with more than 75 percent of all projects being collaborative. In addition, more than 30 percent of the proposals are multi-institutional, connecting researchers from at least two different E^{3}S institutions.

To highlight the multi-institutional nature of the Center for E^{3}S and further increase collaborations between different institutions, the Center leadership introduced a new postdoc program in Period 7: *The Center for E^{3}S Inter-Institutional Postdoc (IIP) Program*. In more detail, each theme will hire an additional postdoctoral researcher. This new postdoc must be hired into a joint position between at least two E^{3}S faculty members from different institutions. Furthermore, the new postdoc must spend research time at the different E^{3}S institutions and it is fully expected that all publications with inter-institutional postdocs as lead authors will have faculty co-authors from at least two different E^{3}S institutions. This program was initiated in the summer of this year and all new postdoc hires were decisions reached by all members of each research theme. So far, themes I, II, and IV already hired their inter-institutional postdocs, with theme III being in the process of bringing in its new postdoc. While these four new postdocs are expected to interact and collaborate with the entire theme, a brief summary of the key faculty representing the new inter-institutional collaborations facilitated by this program is given below:

- Theme I: Postdoc shared between **Ali Javey** (*Berkeley*) and **Jing Kong** (*MIT*) for research on new chalcogenide monolayers with focus on CVD and MOCVD synthesis of 2D transition metal dichalcogenide materials and characterization of types and density of defects in these new semiconductors.
- Theme II: Postdoc shared between **Tsu-Jae King Liu** (*Berkeley*), **David Zubia** (*UTEP*), **Junqiao Wu** (*Berkeley*), and **Jeffrey Lang** (*MIT*) for research on the fabrication and characterization of energy-efficient low-power switches based on the latest NEMS technology developed in the nanomechanics theme. Research responsibilities will include development of new nanomechanical devices, cleanroom-based device fabrication, and characterization of device switching properties.
- Theme III: Plans are in place to hire a postdoc who will be shared between **Ming Wu** (*Berkeley*) and **Eugene Fitzgerald** (*MIT*) for research on nanoLED fabrication. A position advertisement has been posted and applications are reviewed on a rolling basis. It is expected that the inter-institutional postdoc for theme III will start early next year.
- Theme IV: Postdoc shared between **Jeffrey Bokor** (*Berkeley*), **H.-S. Philip Wong** (*Stanford*), and **Vladimir Stojanovic** (*Berkeley*) for research on design and fabrication of new magnetic devices based on ultrafast switching. In more detail, the postdoc will integrate GdFeCo-based magnetic switches on top of CMOS circuits built using advanced 45 nm technology chips obtained from industry foundries.

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

The goal of the nanoelectronics theme (theme I) is to develop a solid-state switch that can be actuated in the milli-Volt range and thus be more efficient than the conventional transistor switch. Among possible alternative switching mechanisms, the tunnel switching mechanism appears to be inevitable. With the miniaturization of devices, following Moore's Law, tunneling is an unavoidable consequence. Tunnel transistors employ tunneling rather than treating it as an unwanted "side effect". Despite promising theory work regarding the steepness, On/Off ratio and conductance of tunnel transistors [1], experimental research failed to yield devices that fulfill all three requirements or that approach predicted performance.

Two main tunnel modulation mechanisms are in play: Tunnel-distance modulation versus density-of-states modulation, also called energy filtering. While the density-of-states modulation mechanism is the desired mechanism, state-of-the-art device results have continued to be disappointing and are more characteristic of the tunnel-distance-modulation mechanism. A characteristic of the tunnel-distance mechanisms is that modulation is steep at low currents, but unfortunately rather shallow at the high conductance (current) density needed for a competitive device. Good conductance density translates directly to clock speed, and cannot be sacrificed. Indeed, prior results display this very characteristic of tunnel-distance modulation; good steepness but only at low current densities [2-5]. Averaged over both low and high current density, under the tunnel-distance-modulation mechanism, a ~50 percent reduction in operating voltage might be achievable, (at best 250 mV), compared to today's conventional transistors,

Since its inception the Center for E^3S has set its goals far below a 50 percent reduction of the operating voltage. In fact, the Center's nanoelectronics theme aims to replace current transistors with a solid-state switch operating in the milli-Volt regime. Nanoelectronics researchers at E^3S thus have focused on elucidating the underlying device physics, as opposed to simple device optimization. Guided by theme leader **Eli Yablonovitch** (*Berkeley*), E^3S nanoelectronics researchers at Berkeley and MIT have shed light on why previous attempts to design and fabricate switches operating on the preferred density-of-states mechanism have failed: In short, this mechanism demands higher materials interface perfection than ever previously required and achieved in solid-state electronics.

The reason for this extreme demand on interface perfection is that tunneling is an interfacial process, proportional to the final two-dimensional density of quantum states in a quantum, which is $dN/dE \sim 10^{13}/(cm^2eV)$ for typical effective masses. Importantly, this desirable tunneling needs to compete with the bandgap defect state density, D_{it}, which is a very important figure-of-merit in electronics science which has the same units $/(cm^2eV)$. For III-V materials, D_{it} is $\sim 10^{12}/(cm^2eV)$. Even in the most favorable material system [21], after decades of research, the best D_{it} which is in Si/SiO_2 interfaces is still $\sim 10^{10}/(cm^2eV)$. As a consequence of this defect density, these materials display "trap-assisted-tunneling" leakage when the switch is supposed to be "Off". This means that, at best, On/Off ratios of only 10-100 can be achieved, while On/Off ratio~10^6 is required for energy efficiency under static leakage. Therefore, even after decades of electronic material investigations, the best interface state-density materials are far from being good enough.

The nanoelectronics research theme of the Center for E^3S has thus embarked on a quest to (1) fully understand interfacial effects and trap-assisted tunneling, and (2) search for new material systems with ultra-low interfacial defect states. Regarding the first goal, the **Antoniadis** and **del Alamo** groups (*MIT*) and the **Yablonovitch** group (*Berkeley*), building on previous works [6,7], have continued in-depth studies of trap-assisted tunneling at both the simulations/modeling and the experimental level. The model system used in these studies are vertical nanowire TFET structures fabricated at MIT. In the current reporting period, the **Antoniadis** and **del Alamo** groups have made further progress in refining etching procedures for reducing nanowire diameter to achieve single-channel III-V vertical nanowire TFETs toward the goal of monitoring individual defects in the nanowire. The experimental data are modeled by the **Yablonovitch** group to gain mechanistic insights into the two-step tunnel leakage process (thermal activation followed by band-to-band tunneling) discovered in the last period. Thus we see the small remaining III-V effort as directed toward fundamental understanding, but not necessarily the ultimate path toward the right form of tunnel transistor.

The major research topic of the nanoelectronics theme is the search for new material systems with ultra-low defect density with the goal to achieve proper density-of-states modulation tunnel transistors, exhibiting all the desired properties; high On/Off ratios, steep modulation, and high conductance (current) densities. In this regard, the nanoelectronics theme has intensified research in both two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs) as low-defect density semiconductor materials. In the current period, the 2D-TMDC research efforts led by Berkeley researchers **Ali Javey** and **Eli Yablonovitch** has been strengthened by the addition of **Jing Kong** (*MIT*). 2D-TMDCs are excellent material systems because of their completely covalently bonded structure, minimum surface roughness, and low density of dangling bonds and surface defects in single-layer materials. In addition, as recently demonstrated by the **Javey** group, it is possible to "heal" defects through appropriate chemical treatments [8]. Together, the **Javey** and **Kong** groups work on characterizing new TMDC materials with near-zero defect densities, devise methods of bottom-up grown high-quality TMDC layers, and to integrate these 2D semiconductors into device structures.

Another approach toward bottom-up synthesis of nearly perfect semiconductor materials (absence of defects) has been led by organic chemist **Felix Fischer** (*Berkeley*). Since this research project started at the beginning of last year's reporting period, the **Fischer** group has made good progress in the bottom up synthesis of hybrid graphene nanoribbon (GNR) heterostructures. These are semiconductors quite distinct from graphene itself, which is a semimetal. The semiconducting property arises from lateral electron quantum confinement effects in the one-dimensional nanoribbon structure. Initial structures synthesized by the **Fischer** group have focused on incorporating molecular quantum dots with a narrow tunneling barrier into individual GNRs acting as conducting wires. To develop a fundamental understanding of how to assess the energy level structure and to guide the synthetic efforts, Berkeley theoretical physicist **Steven Louie** joined the nanoelectronics theme. The **Louie** group brings extensive expertise in first principles quantum mechanical calculations and together with the **Yablonovitch** group has been assisting the **Fischer** group in the rational design of functional device architectures that would rely on quantum tunneling junctions. Initial computational results show good agreement between experimental scanning tunneling microscopy measurements and calculated band structures of quantum dot embedded GNRs.

In the following, details are provided for the Period 7 nanoelectronics theme research efforts in:

Ia. Vertical Nanowire TFETs
Ib. Layered Chalcogenide TFETs
Ic. Graphene Nanoribbon Quantum Tunneling Structures

Ia. Vertical Nanowire TFETs

Research efforts on III-V materials-based TFETs have continued in the **del Alamo** and **Antoniadis** groups (both *MIT*) since previously fabricated III-V heterojunction TFETs have proven to be excellent model systems to study the underlying physics of tunneling in semiconductors, while revealing the issue of defect assisted tunneling in the Off-state [6]. With recently developed very high aspect ratio nanometer-scale etching technology capable of reaching sub-10 nm diameters, for the first time, single-mode InGaAs vertical nanowire TFETs should be possible, possibly permitting individual defects to be observed in current-voltage spectroscopy.

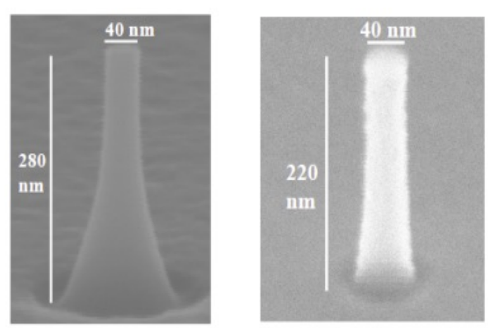


Figure 2.2. SEM images comparing the verticality of earlier generation (2013, ref. [23]) nanowires (left) and new generation nanowires (right) fabricated by improved RIE methods.

In Period 7, the **del Alamo** group has continued its research project for the development of steep-subthreshold slope vertical nanowire TFETs based on the InGaAs system. The unique feature of **del Alamo**'s approach is that the vertical nanowire geometry is fabricated by a top-down approach—in contrast to typical bottom-up approaches (via epitaxial growth), which are less flexible. In this period, the **del Alamo** group has made excellent progress in improving the verticality of the InGaAs nanowires, enabled by refinement of the III-V reactive ion etching (RIE) technology. Figure 2.2 gives a comparison of an earlier generation nanowire [23] with a nanowire fabricated by the new RIE technology. An interesting aspect of the new devices is that the improved verticality of the nanowire sidewalls and the uniformity of its diameter has resulted in a significant mitigation of the strong asymmetry that was observed in the subthreshold characteristics in earlier generations of transistors, as shown in Figure 2.3. Devices fabricated in 2013 exhibited a large change in the saturated subthreshold swing (S_{sat}) and the drain-induced barrier lowering (DIBL) when the source and drain are swapped (BES: source at bottom; TES: source at top). This is due to the different diameters at the top and the bottom of the nanowire. In contrast, the more uniform devices fabricated by the improved RIE method displayed no asymmetry when swapping source and drain, and both S_{sat} and DIBL are substantially better.

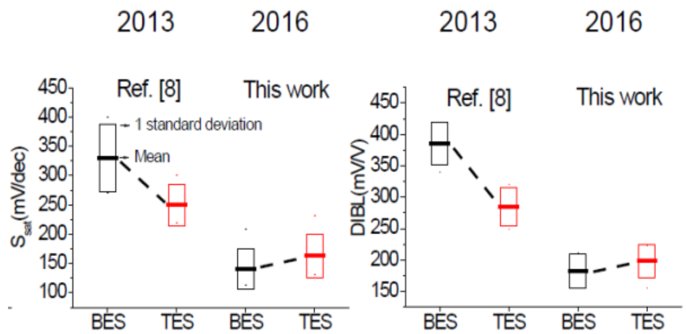


Figure 2.3. Comparison of asymmetry in the subthreshold characteristics of transistor devices of earlier generation nanowires (2013; ref. [23]) and new generation nanowires (2016). Compared are saturated subthreshold swing (S_{sat}) and the drain-induced barrier lowering (DIBL) when the source and drain are swapped (BES: source at bottom; TES: source at top).

MOSFETs are an excellent testing ground for new fabrication and processing methods [24-26]. While working vertical nanowire FETs down to 20 nm diameter were fabricated, the heterostructure, the contact resistance of the top contact was too high. Nevertheless, devices with 40 nm diameter nanowires exhibited outstanding transport and subthreshold characteristics (Figure 2.4). This is partly due to improved quality of the new ALD oxide. In fact, in terms of the balance between transconductance and subthreshold swing, the latest results from the del Alamo group exceed the best vertical nanowire InGaAs MOSFETs reported to date that were fabricated by a bottom-up technique.

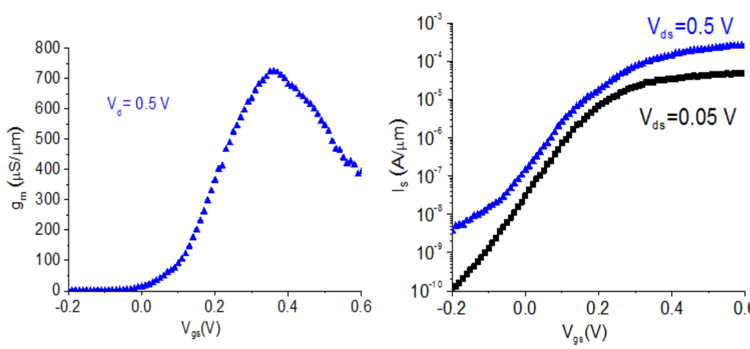


Figure 2.4. Transport and subthreshold characteristics (transconductance and subthreshold swing) of vertical nanowire MOSFETs with 40 nm diameter nanowires.

The **del Alamo** group has also developed a new alcohol-based digital etch scheme that enables trimming of the InGaAs nanowires down to below 10 nm. This is the target range for the E^3S nanoelectronics program since InGaAs vertical nanowires TFETs with with sub-10 nm nanowire dimensions can support a single 1D subband. As has been shown by the **Yablonovitch** group's modeling work, single 1D subband devices will give new insights toward the goal of elucidating the fundamental physics of tunneling transistor devices. A major challenge in the fabrication of sub-10 nm nanowire TFET devices this is that nanowires become extremely fragile at these dimensions. The new digital etch approach has greatly improved the survivability of extremely thin nanowires. For the first time, a 5 nm diameter InGaAs vertical nanowire has been achieved by the del Alamo group (Figure 2.5). Furthermore, a new RIE chemistry has been developed that is capable of etching InGaAs- and InGaSb-based heterostructures at a similar rate with high aspect ratio. In addition, in both systems smooth sidewalls were obtained. This new etching technique will be key for the future fabrication of InAs/GaSb vertical nanowire TFETs.

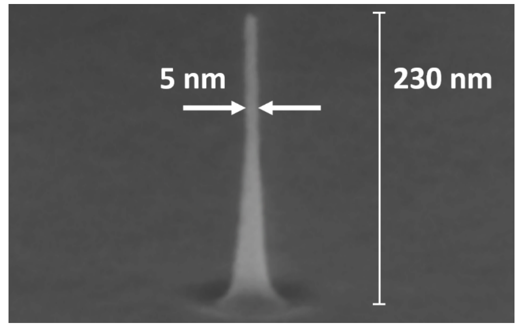


Figure 2.5. SEM image of a 5 nm diameter InGaAs nanowire fabricated by a new digital etch approach.

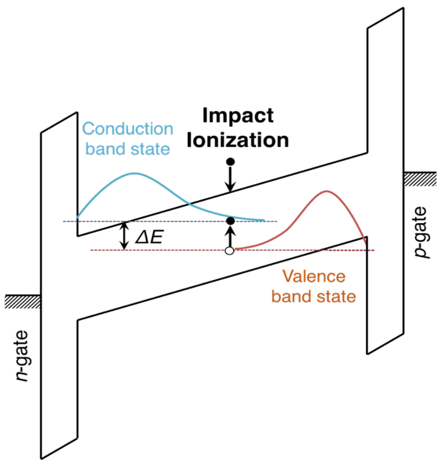


Figure 2.6. Band diagram of bi-layer TFET illustrating the impact ionization leakage current in the OFF-state (ΔE > 0).

In parallel, the **Antoniadis** (*MIT*) and **Yablonovitch** (*Berkeley*) groups in collaboration with former E^{3}S student James Teherani (now assistant professor at Columbia University) and our industrial partner *IBM* investigated the parasitic leakage current due to Auger generation [15]. This was a previously unrecognized leakage mechanism in TFETs. This is an intrinsic mechanism that cannot be mitigated with improved material quality or better device processing and is key to explain the discrepancy between TFET experiments and simulations. The mechanism is illustrated in Figure 2.6, which shows the band diagram in the tunneling direction of a bi-layer TFET, which operates by controlling the flow of electrons from the valence band of the p-type quantum well to the conduction of the n-type quantum well. When the bands do not overlap, no tunneling current is expected. However, in spite of the energy misalignment, the electron wavefunctions in the two bands overlap spatially. This allows a transition to occur from the valence band to the conduction band when an energy equal to (or greater than) their difference ΔE is supplied externally. The requisite energy can readily be provided by free carriers in either of the two quantum wells, some of which possess kinetic energy greater than ΔE. This process is identical to impact ionization, and it is also the inverse process of Auger recombination. This work exposed the intrinsic link between the Auger and band-to-band tunneling rates, highlighting the difficulty of increasing one without the other. For common semiconductors like Si, the group estimated this effective On/Off ratio to be ~10^3 to 10^5. Both the band-to-band tunneling probability and the impact

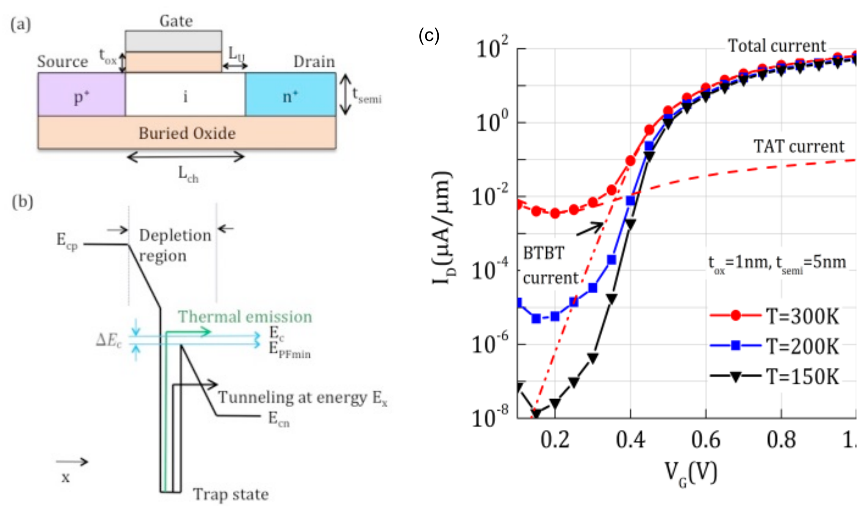


Figure 2.7 a) Top-gate homojunction TFET model structure. **b)** Energy band diagram of model structure. **c)** Temperature-dependent current-voltage characteristics.

ionization leakage scale with the overlap of the wavefunctions. From this link, it is shown that Auger generation, contrary to the extrinsic trap-assisted-tunneling imposes an intrinsic limit on ultimate tunnel FET On/Off ratio, but that this could be mitigated by clever design.

Regarding trap-assisted-tunneling (TAT), the **Antoniadis** group developed a model for this process in a top-gate homojunction TFET (Figure 2.7a). This group showed that in the presence of surface interface traps at common densities, D_{it}, TAT is the principal mechanism of leakage current in TFET before band-to-band tunneling (BTBT) is initiated (Figure 2.7b). With a modified Shockley-Read-Hall formalism, we show that the TAT obscures the steepest part of the BTBT current for realistic trap densities as given in Figure 2.6c, in which midgap D_{it} is assumed to be $5x10^{12}/(cm^2 eV)$. Through a multi-phonon process, an electron (or hole) can be emitted to a trap state followed by tunneling into the conduction band (or valence band for hole), the mechanism of TAT. The minimum subthreshold swing is a combined result of the trap density, intrinsic sharpness of the band edge (Urbach tail), and other material parameters. This study showed that the TAT current is greatly enhanced at high electric field in the tunnel barrier, in the same way as the desired BTBT current. This model is applicable to III-V, silicon top-gate TFETs, and other structures as well.

Ib. Layered Chalcogenide TFETs

In previous periods the nanoelectronics theme of E^3S has demonstrated practically functioning TFETs from 2D materials. However, the team around **Ali Javey** and **Eli Yablonovitch** (both *Berkeley*) quickly realized that a sharp subthreshold swing in the density-of-state switching scheme requires sharp conduction/valence band edges with very little to no tail states. This can only be achieved by highest quality materials of which transition metal dichalcogenides (TMDCs) are a candidate. 2D-TMDCs such as MoS_2 and WS_2 are particular attractive due to their high potential for structural perfection; i.e. extremely low defect densities. Unfortunately, as-exfoliated and as-grown 2D-TMDC materials are far from being defect-free. The **Javey** group has been using quantitative photoluminescence (PL) spectroscopy as a metric to measure material quality as it is drastically affected by the defects in the material structure. On this platform they were able to find an air-stable, chemical surface defect passivation scheme (an organic superacid) for exfoliated 2D MoS_2 that resulted in internal quantum yield efficiency approaching 100% [8].

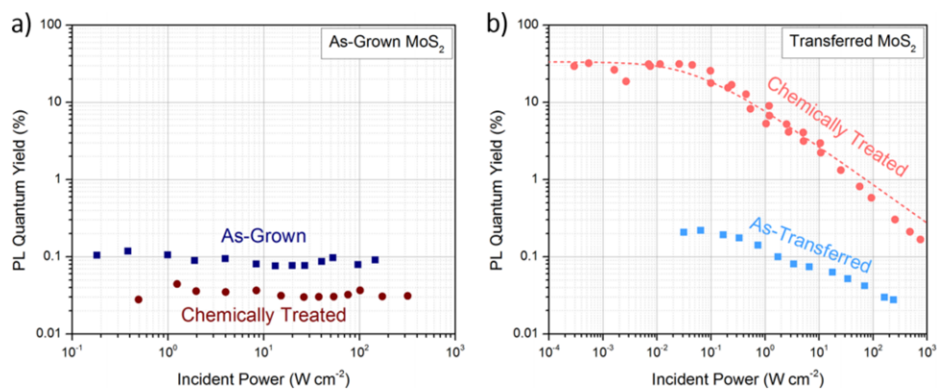


Figure 2.8. Demonstrated superacid treatment on CVD grown samples only after the sample is relieved of its native strain due to the growth process itself via flake transfer.

In a collaborative effort between the **Javey** (*Berkeley*) and the **Kong** (*MIT*) groups this defect passivation method was also successfully applied to CVD-grown MoS_2. Interestingly, the super-acid treatment was not at all effective for as-grown CVD samples (grown in the **Kong** group), apparently due to strain interaction with the substrate. However, once released from the substrate the super-acid treatment increased the internal quantum yield efficiency of CVD-grown MoS_2 by more than two orders of magnitude (Figure 2.8). Furthermore, it was found that for CVD-grown samples the treatment is most effective in samples having more sulfur deficiency. The fact that in CVD samples the quantum yield increases only to ~30% percent efficiency (compared to near 100% in exfoliated natural samples) is indicative of the presence of different types of defects in CVD-grown samples.

Recently, the **Javey** group successfully applied the super-acid treatment method also to other 2D-TMDC, including WS_2 [27]. Using a combination of photoluminescence lifetime and quantum yield efficiency studies, they were able to fully characterize and understand edge-recombination in 2D WS_2. From these studies they were able to determine crucial parameters such as exciton diffusion length and non-radiative edge recombination lifetime, as shown in Figure 2.9. Current research efforts in the **Javey** and **Kong** groups focus on fully characterizing the defects in CVD-grown MoS_2 and on a search for additional passivation methods. In particular, passivation of edge defects, either through chemical treatment or growth of a cladding layer, will be crucial for the development of high-performance devices.

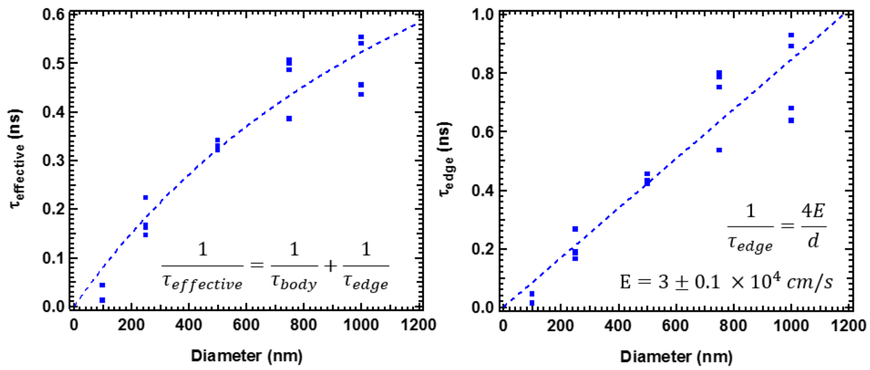


Figure 2.9. Edge recombination and edge recombination lifetime probing of WS_2 – a metric called edge recombination velocity is used to characterize edge defect level.

Ic. Graphene Nanoribbon Quantum Tunneling Structures

This project was initiated in Period 5 with the goal of placing attention squarely on novel materials systems capable of producing the most perfect molecular scale device structures—a pre-requisite for future progress in ultra-low voltage switching. The experimental aspects of the graphene nanoribbon project continue to be led by the **Fischer** group (*Berkeley*) with broad theory support by the **Yablonovitch** group and the **Louie** group (*Berkeley*). The **Louie** group joined the Center for E^3S at the beginning of this period and brings extensive expertise in ab initio calculations of electronic structures into the nanoelectronics theme.

The **Fischer** group has continued to develop bottom-up synthesis strategies for heterostructure graphene nanoribbons (GNRs). In Period 7, particular emphasis was directed towards integrating molecularly defined quantum dots (QDs) with a tunnel barrier in-between, and flanked by two atomically defined tunneling barriers into metallic GNR connecting wires (Figure 2.11). Based on the **Fischer** group's expertise with bottom-up fabricated graphene nanostructures, molecular precursors for QDs were synthesized from porphyrin derivatives that are structurally compatible with a series of molecular precursors for GNRs. The unique molecular structure and highly tunable electronic levels of porphyrin-derived QDs enable rational fine-tuning of the structural and electronic properties between the two quantum dots and the connecting semi-metallic molecular wires. To characterize the local electronic structure and the alignment of energy states in fabricated GNR quantum tunneling junctions, the **Fischer** group uses high resolution scanning probe microscopy. Ultimately the strategy will be to use chromatography to purify the desired molecular device structures, to generate highly reproducible energy levels from molecular scale device to molecular scale device.

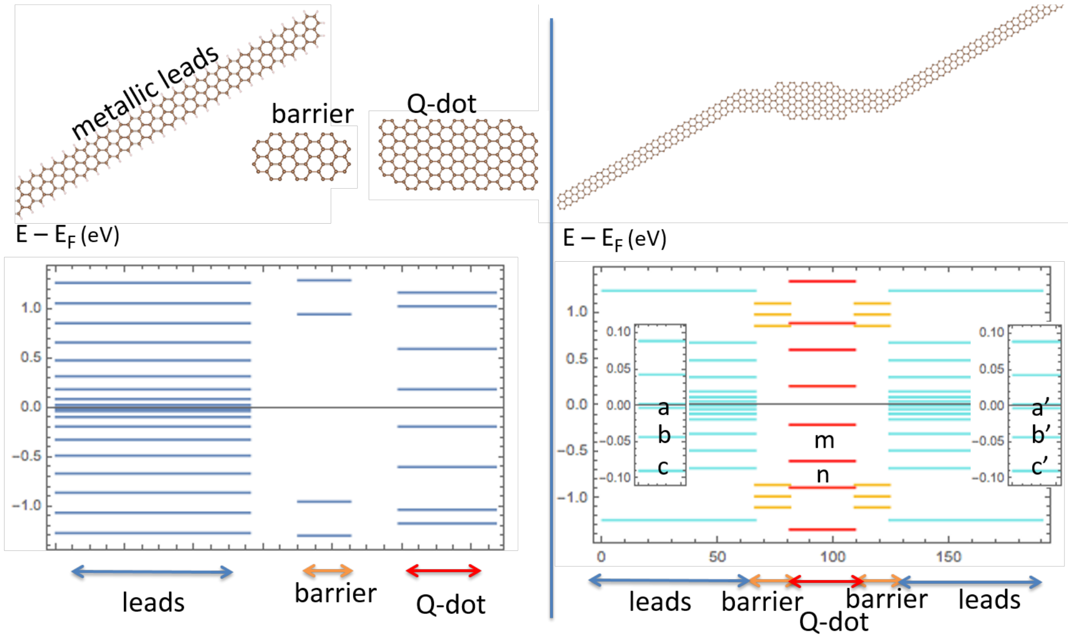


Figure 2.11. Top: Molecular model structures of GNR-based metallic leads, barrier section, and QD (left) and the molecular structure of the connected system (right). **Bottom:** Corresponding calculated energy levels of the isolated components (left) and the connected, fully integrated system (right).

The design of these structures was guided by density functional theory (DFT) calculations by the **Louie** group, using model Hamiltonian methods as well as first-principles calculations. A model structure and calculated energy band structures for isolated parts (semi-metallic leads, barrier section, and quantum dots) and a sample connected, fully integrated system is given in Figure 2.11 left and right, respectively. While the preferred structure and doping mechanism is still subject to revision, the Louie group has considered several kinds of GNRs with different geometric and doping configurations to serve as leads, barriers, and QDs of the desired device. Based on these systems, including pristine armchair/zigzag GNRs and doped GNRs, we have identified distinct electronic properties. For example, the zigzag GNRs show a near metallic character useful for wired leads, whereas deterministically boron-doped GNRs provide a tunable band gap and tunable barrier heights. In the QD region, calculations indicate controllable broadening owing to coupling to the metallic wired regions.

Recently, the **Fischer** and **Louie** groups have also applied computational methods in collaboration with the **Salahuddin** group (*Berkeley*) to analyze the performance of the fabricated device architectures. These calculations are the basis for discussions with the **Yablonovitch** group toward rationally guiding the design of improved generations of bottom-up fabricated QD tunneling junctions.

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

The defining ultimate goal of the nanomechanics theme is the demonstration of reliable nano-electromechanical (NEM) switch (or relay) operation at or below 10 mV. The key challenge toward achieving this goal has remained the minimization, or even elimination, of the contact adhesion energy since contact stiction gives rise to hysteresis voltage (V_H). Hysteresis voltage, in turn, limits minimization of the operating voltage (V_{DD}) and switching energy of an electromechanical switch (Figure 2.12).

In this reporting period, significant progress has been made to lower the contact adhesion energy of electromechanical switch designs using different approaches, including the design for non-pull-in-mode operation [16], the application of an anti-stiction molecular electrode coating, and the "squitch" concept (in reference to squeeze-switch) [9]. The latter is a NEM switch designed to conduct via tunneling through an electromechanically compressed gap supported by a molecular monolayer. In addition, in this period, the nanomechnics theme has intensified research efforts in piezoresistive NEM switches by straining 2D chalcogenide layers using electromechanical actuators. In short, in this "stritch" device (in reference to stretch-switch) the stretching of the semiconductor chalcogenide material causes tensile strain and concomitant change in its bandgap and conductivity.

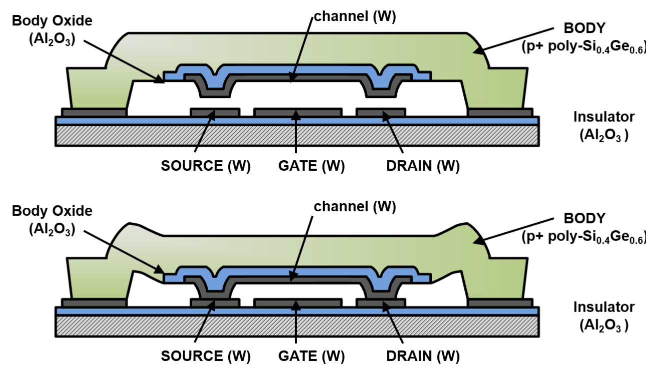


Figure 2.12. Schematic illustration (cross-sectional view) of a nano-electromechanical (NEM) switch at different operating voltages.

In the following, details are provided for the Period 7 nanomechanics theme research efforts in:

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

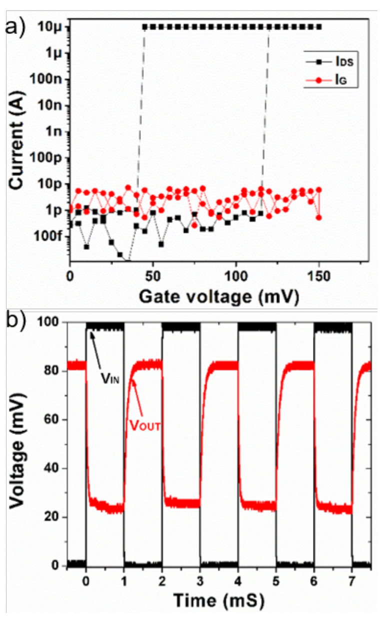


Figure 2.13. a) Measured *I-V* for a body-biased relay. **b)** Corresponding measured inverter voltage waveforms.

IIa. Ultra-Low-Voltage Relay Design

Nanomechanics theme leader **Tsu-Jae King Liu** (*Berkeley*) and her team focused Period 7 research efforts on the minimization of hysteresis voltage of electro-mechanical switches (relay) through new device design allowing for non-pull-in-mode operation. Relay operation with less than 100 mV hysteresis voltage was achieved by designing the relay to have an as-fabricated contact gap size that is less than one-third of the as-fabricated actuation gap size. With body biasing, very low voltage operation is possible, as shown in Figure 2.13a. 100 mV operation of an inverter circuit comprising a body-biased relay functioning as a pull-down switch and a resistive load was successfully demonstrated, as demonstrated in Figure 2.13b. It should be noted that the output voltage swing here is limited because the oscilloscope input resistance (1 MΩ) is not infinite and the relay contact resistance is relatively large (~100 kΩ) due to lower contact force for low-voltage operation. These are not expected to be issues for relay-based integrated circuits because the Off-state resistance of a relay (vs. the load resistance in the inverter circuit) is much larger than its On-state resistance, and the input impedance of a relay (vs. an oscilloscope) is essentially infinite.

In Period 7, the **King Liu** group also designed vertically oriented relays to be fabricated using a standard 65 nm CMOS process, using the back-end-of-line (BEOL) interconnect (metal) layers. Specifically, body-biased logic relays and single-pole-double-throw (SPDT) relays for non-volatile memory were designed and simulated using Coventorware MEMS+ software. The designed relays will be fabricated by IBM and the devices will be released at UC Berkeley using dry and wet etching capabilities in the Marvell Nanofabrication Laboratory. Figure 2.14 shows an example of a simulated BEOL relay structure and the cross-sectional schematic of the metal layer stack after selective removal of the interlayer dielectric material (oxide) to release the movable beam.

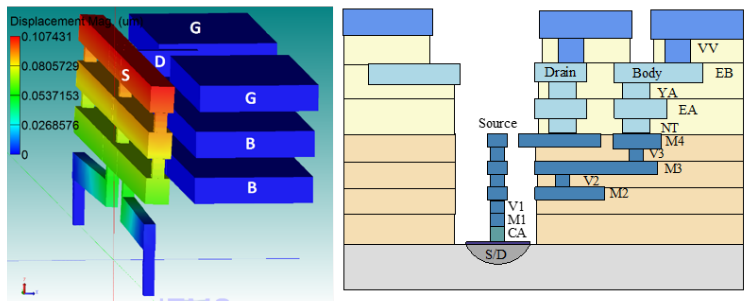


Figure 2.14. Left: Simulated structure of vertically oriented body-biased relay. **Right:** Cross-section after sacrificial oxide etch.

The system integration efforts led by the group of **Vladimir Stojanovic** (*Berkeley*) has provided a path to quantifying the benefits of the emerging device technologies in the nanomechanics theme at the circuit/system level. In addition, system integration provided guidance to the device designers on which device design parameters are critical to improve at the system level. For this, the **Stojanovic** group has created circuit-level device models that are versatile-enough to capture the most important characteristics of the underlying devices yet simplified-enough to enable fast circuit-level simulation. A challenge for system integration efforts has been to invent the circuit topologies that will get around or alleviate some of the challenges facing the underlying device technology, such as long mechanical delays in relay devices. In this period, the **Stojanovic** group has continued its collaboration with the **King Liu** group and analyzed the application of NEMory relays in creating dense, low-energy nonvolatile memory (NVM) arrays with pattern-matching capabilities (Figure 2.15). In addition, efforts are underway to evaluate the energy/area/timing analysis of non-volatile reconfigurable logic based on NEMory devices [28].

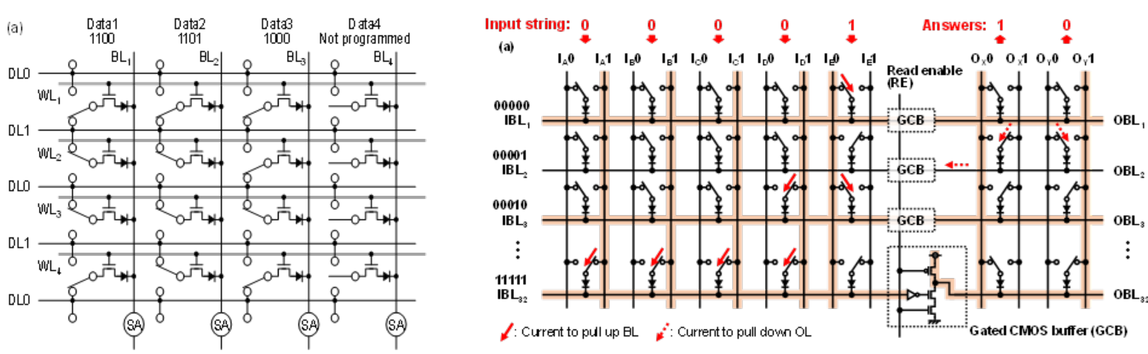


Figure 2.15. Left: NVM pattern-matching memory. **Right:** NVM reconfigurable logic.

In a collaborative project between the **J. Wu** and the **King Liu** groups (both *Berkeley*), an alternative approach for lowering the contact adhesion energy was pursued by using an anti-stiction molecular coating [29]. This project uniquely incorporates the "squitch" idea (see below) into a conventional electrostatic relay design. For this, a vapor-phase molecular coating process was successfully transferred from the **Squitch** group at *MIT* to *Berkeley* and relays were coated with a molecular self-assembled monolayer (SAM) soon after being released. Figure 2.16a compares measured current-vs.-voltage (I-V) characteristics before and after coating with the SAM molecule perfluorodecyltriethoxysilane, PFDTES. Note that although V_H is reduced by the PFDTES coating, the transitions between Off and On states are less abrupt, i.e. the subthreshold swing is increased. Therefore, a larger gate voltage swing is needed to fully switch the relay On. However, if a smaller On/Off current ratio (e.g. 10^4) is sufficient, then the coated relay can be operated with a smaller gate voltage swing, as demonstrated in Figure 2.16b. It should be noted that this is in contrast to an abruptly switching relay, which cannot be operated with a gate voltage swing that is smaller than V_H. By applying a body bias to bring the molecular coatings on the opposing conducting electrodes into contact, a metal-molecule-metal "squitch" structure is effectively achieved.

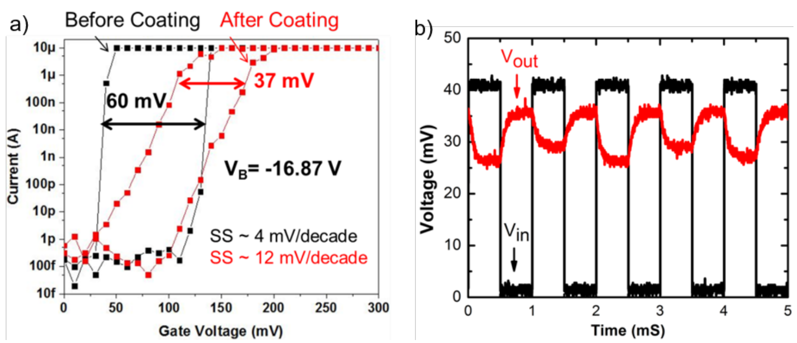


Figure 2.16. a) Effect of PFDTES coating on relay *I-V*. **b)** Measured coated-relay inverter waveforms.

IIb. Squitch: Molecular Squeeze-Switch

The research groups of **Vladimir Bulovic**, **Jeffrey Lang** and **Tim Swager** (all *MIT*), the **Squitch** group, have continued to refine and optimize the squitch fabrication process, in particular with respect to high-yield fabrication that can be scaled to circuit-level complexity. During the last two reporting periods the **Squitch** group realized that the metal (gold) relay electrodes that define the squitch gaps cannot be reliably formed by conventional micro-scale deposition techniques such as e-beam deposition or sputtering. The resulting electrode surfaces were too rough as sub-nanometer roughness is required to define nanometer gaps. An alternative fabrication process was developed based on chemical synthesis of atomically-smooth crystalline gold nanoplates and nanocubes that serve as the stationary and moveable electrodes, respectively. In the current period, the growth process and uniformity of the nanoplates has been significantly improved to facilitate reproducible assembly of nanogaps. During this assembly process, the nanoplates are suspended at the interface between two immiscible solvents. They are chemically treated, causing them to descend as the solvents dry into a closely-packed single layer on a glass substrate while maintaining a 20-nm or so lateral separation, after which gold interconnects and contact pads are deposited over their edges securing them in place (Figure 2.17). This assembly process was recently improved by introducing the optimized two-step growth of a hydrophobic alkanethiol layer to functionalize the nanoplate surfaces. The directed assembly

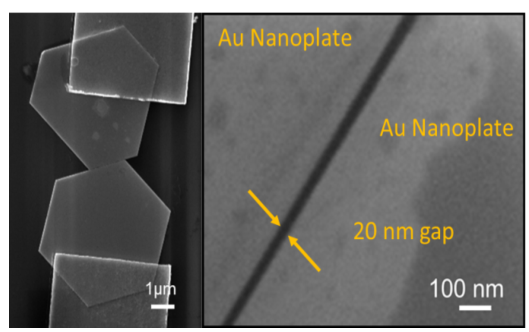


Figure 2.17. Left: Two gold nanoplates side-by-side on an oxidized silicon substrate and held in place by deposited gold interconnects. **Right:** An expanded view of the plate-to-plate gap showing in detail the plate-to-plate alignment and the smoothness of the plate-to-plate gap.

was also improved by optimizing the surface properties of the substrate used in assembly, the assembly temperature, and the ratio of the two immiscible solvents used. Finally, the density of gaps, and hence squitches, was further improved by the uniformity of the nanoplates.

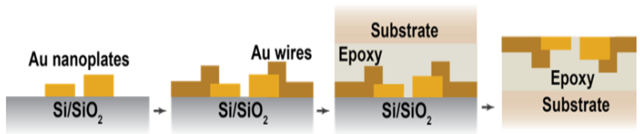


Figure 2.18. Schematic of the peeling process for fabrication of a planar array of gold nanoplates.

To compensate for the non-uniform thickness of nanoplates, which would result in an unacceptable step in height across the gap, the **Squitch** group developed a new post-assembly processing technique. This method is given in Figure 2.18 and takes advantage of the fact that the bottom surfaces of the nanoplates against their substrate are co-planar. Therefore, after drying, the nanoplates are coated with an epoxy-like binding layer to hold them in place, and peeled as a continuous layer off the original substrate. This reveals an organized planar array of closely-spaced gold electrodes that are electrically isolated and atomically smooth. As described above, the gold wiring is currently used to form contact pads and interconnects to the nanoplates. However, the same wiring could be also used to connect different squitches into circuits. In summary, the fabrication process by which gold nanoplates are assembled into squitch electrodes is now considerably more robust, repeatable and uniform than it was a year ago, and it provides a greater spatial density of electrodes. Moreover, three-terminal squitches with a recessed gate to prevent gate tunneling currents can be fabricated using a sacrificial layer beneath the nanoplate that becomes the gate electrode, as shown in Figure 2.19. The sacrificial layer elevates the nanoplate above the glass substrate, and is then removed after peeling. During the past year the **Squitch** group developed this fabrication process extension, and demonstrated the ability to recess the gate electrode by at least 4 nm as shown in the surface topography scan. This is sufficient to prevent gate tunneling.

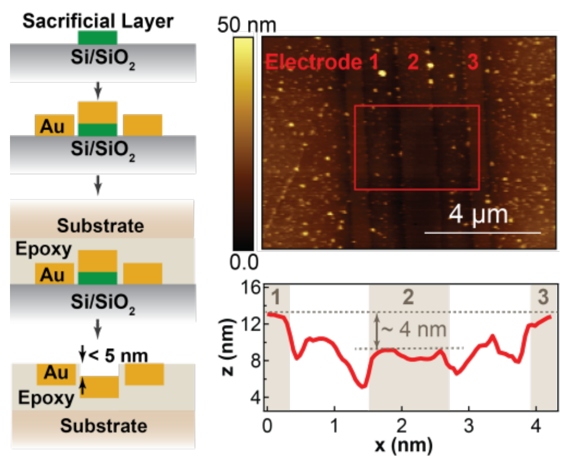


Figure 2.19. Left: Extension of the electrode fabrication process to implement a recessed gate. **Right:** Surface topography scan indicating that the gate is recessed by approximately 4 nm.

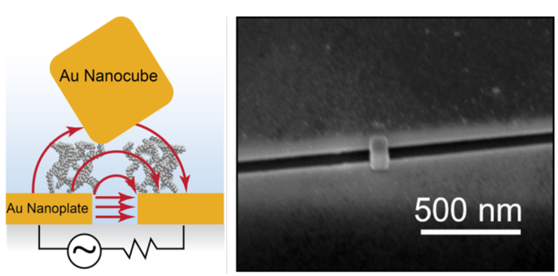


Figure 2.20. Left: Illustration of the dielectrophoretic nanocube location process. **Right:** A single 100-nm gold nanocube located over a plate-to-plate gap as would be required for the fabrication of a two-terminal squitch. A molecular monolayer anchors the nanocube to the nanoplates.

The final two fabrication processes are (1) growth of the molecular monolayer that fills the squitch gaps and supports the moveable electrodes, and (2) placement of gold nanocubes on top of the nanoplate gap so as to straddle boundaries between nano-plates. Regarding the first process, the **Squitch** group uses thiol chemistry to attach alkane or polyethylene glycol to the gold electrodes. Nanoscale IR spectroscopy was used to confirm that molecular monolayer formed only over the electrodes and to monitor their uniform growth. For the placement of gold nanocubes across the nanoplate electrode gap, the Squitch group developed a new method. This method is based on the discovery that electrical excitation of the electrodes will more reliably attract the gold nanocubes to their desired location through a process that resembles dielectrophoresis, as shown in Figure 2.20 (left). Dielectrophoresis would ordinarily attract many cubes to straddle one gap. However, by placing a large resistance in series with each gap the first cube attracted shorts the gap thereby stopping the local dielectrophoresis process. This process enabled the fabrication of an array of single-cube squitches. One such two-terminal squitch is shown in Figure 2.20 (right). Here, the gold nanocube is suspended above the nanoplates by a molecular monolayer that has also chemically assisted dielectrophoretic location of the nanocube.

The **Squitch** group has also experimentally measured the tunn eling currents through a two-terminal squitch fabricated using the process described above. These squitches have contained both alkanethiol and polyethylene glycol thiol molecular layers. An example of the measured electrical behavior is shown in Figure 2.21. Note that the figure shows several cyles of excitation over increasing and decreasing applied voltage for two different experiments; the different experiments involve squitches with different gaps. The repeatability of the conduction cycles is substantially improved over what we have measured and reported in past years.

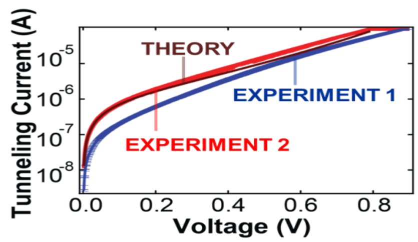


Figure 2.21. Several cycles of tunneling current for two squitches (red and blue) with different gaps. A theoretical current curve is shown for the second experiment (red).

IIc. Stritch: 2D Chalcogenide Stretch-Switch

Initial research by the **Zubia** group (*UTEP*) on strained transition metal dichalcogenides (TMDCs) using a MEMS actuator showed promise to achieve large (~10^6) resistance modulation. This is due to the change in band gap as a result of mechanical strain (deformation potential) [30]. MoS_2 monolayers experimentally exhibit a ~1.9% increase in bandgap when compressively strained by 1.9%. Conversely, it is predicted that its bandgap will decrease to zero when subjected to 11% tensile strain [31]. Importantly, TMDCs can withstand a high degree of strain; for example, MoS_2 has shown exceptional strength with a fracture point at 11% tensile strain. Figure 2.22 gives a perspective view of the device showing a TMDC suspended between a fixed stud (drain) and flexible cantilever (source) in a "stritch" device (in reference to stretch-switch). When a voltage (V_{GS}) is applied between the fixed gate and source, an electrostatic force displaces the cantilever away from the drain. The cantilever displacement causes tensile strain in the TMD and concomitant change in its bandgap and conductivity. In this design, adhesive forces are avoided while the attractive van der Waals force between the gate and source is exploited for mechanical gain.

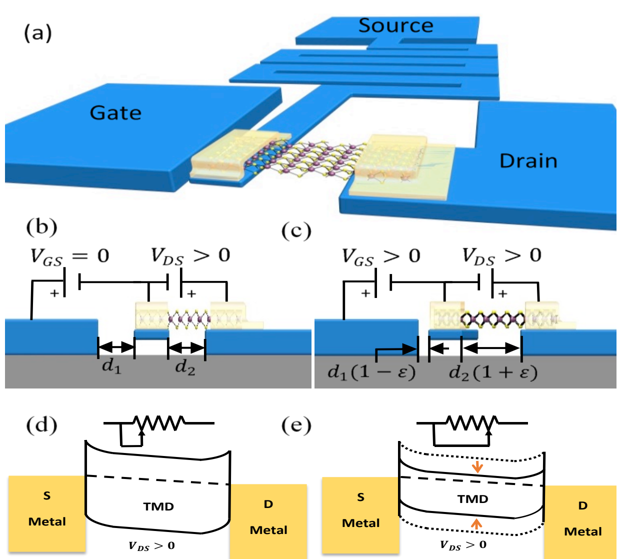


Figure 2.22. a) Isometric view of stritch at ON state; cross-sectional views of the device at OFF **(b)** and ON **(c)** states. TMD band diagram of the **d)** OFF state and **e)** ON state illustrating a band gap reduction due to strain.

In a collaborative effort, the **Zubia** group worked closely with the **King Liu** and **Javey** groups (both *Berkeley*), investigated the electronic properties (bulk and interface) of TMDCs under tensile strain via MEMS actuation for low-voltage switching. A key outcome in this period has been experimental proof-of-concept of the stritch device. Another key accomplishment was the modeling of the device which incorporates mechanical and electronic aspects. Experimental conductance modulation of the MoS_2 stritch device was repeated and successfully modeled as shown in Figure 2.23 (left). Stritch devices with 2 and 3 monolayers of MoS_2 were also fabricated and tested. Simulation using only the width of the TMDC as a fitting parameter showed good agreement with experimental results. Modeling predicts that a stritch with a steepness of 13 mV/dec while maintaining an ON/OFF ratio of 10^6 can be achieved with a TMDC width of 8.5 nm. The Zubia group also conceptualized a stritch-based inverter was conceptualized and modeled as shown in Figure 2.23 (right). Since electrostatic force is ambipolar, the device can be used to implement inverting and non-inverting digital and analog circuitry.

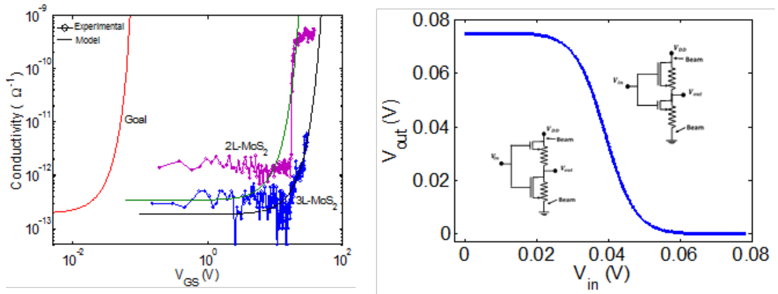


Figure 2.23. Left: Experimental and modeled σ-VGS characteristics of MoS_2 stritch devices. **Right:** Transfer function and circuit diagram of stritch-based inverter.

Current and future stritch research efforts will encompass experimental work as well as device modeling The goal is to experimentally assess how close the performance of a piezoresistive NEM switch can approach the modelling prediction of 40 mV activation voltage and an On/Off ratio of 4 orders of magnitude using MoS_2 or WS_2 TMDC materials.

The goal of the nanophotonics theme is to enable on-chip optical communication between electronic switches at unprecedented efficiency levels. In fact, nanophotonics theme researchers pursue the ultimate goal of experimentally reaching the quantum limit of photons-per-bit in a data-link. This will require reduction of photons per bit from currently used 20,000 to possibly as low as 20 photons/bit. Reaching the quantum limit in terms of photons-per-bit in an optical communications data-link imposes tremendous challenges on choice of materials, nanofabrication of optical components, and their on-chip integration. Ultra-efficient light sources and ultra-sensitive detectors need to be developed and miniaturized to be comparable to the size of transistors. Integration of the optical components in waveguides is also part of the challenges of nanophotonics research.

To meet this goal, the Center for E^3S strives to improve energy efficiency and sensitivity of both the emitter and the photoreceiver. Central to the Center's nanophotonics research goals has been the demonstration that spontaneous emission from antenna enhanced nano-LEDs can be faster and more energy efficient than the stimulated emission of lasers, the ubiquitous light source in optical communications today [10]. Major advances toward this goal have recently been achieved by demonstrating spontaneous emission enhancements of more than 300 times under optical excitation. In this period, >100-times increase in the spontaneous emission rate under electro-excitation was achieved—the first time that antenna spontaneous emission enhancement has been observed under electrical injection. This surprising result has reaffirmed the theme's strategy of introducing optical antenna enhanced spontaneous light emitters for energy-efficient short distance on-chip optical interconnects.

At the systems level, photoreceiver research is of equal importance to the novel antenna-LED transmitter. We need to achieve a more sensitive photo-receiver than is currently available. Simple direct detection is required for short on-chip optical communications links. We have performed a first principles analysis of the physics and circuit principles required for sensitive direct detection. Unsurprisingly, the photodetector must be very small and have the lowest possible capacitance. As part of the Center's integrated systems level approach, we have found that significant changes must be adopted in the receiver circuitry.

In the following, details are provided for the Period 7 nanophotonics theme research efforts in:

IIIa. Antenna-Enhanced III-V nanoLEDs
IIIb. Chalcogenide nanoLEDs
IIIc. Systems Level Photo-Receiver Innovation

IIIa. Antenna-Enhanced III-V nanoLEDs

High-speed antenna-LEDs show great promise as fast, small, and efficient optical emitters for on-chip optical interconnects. The overall goal of this collaborative project between **Ming Wu** and **Eli Yablonovitch** (both *Berkeley*) and **Eugene Fitzgerald** (*MIT*) has been to demonstrate multi-GHz direct modulation rate of III-V antenna-LEDs with high efficiency. In previous research periods progress toward large enhancement of spontaneous emission by coupling an electrically-pumped nanoLED active region to an optical antenna was demonstrated [11]. In this research period, a milestone was achieved by demonstrating a >100-times spontaneous emission enhancement in electrically-injected III-V nanoLED [12,32]. Device structure and experimental results are shown in Figure 2.24. This result was achieved through optimization of antenna design, process improvements, and device scaling. Furthermore, design and growth of epitaxial wafer material with significantly improved quantum efficiency was achieved.

A detailed analysis of our antenna LED design indicates that the requirements for edge passivation of the III-V antenna-LED can be lessened, much as they are for ridge lasers in which stimulated emission competes successfully against non-radiative edge recombination. In the case of the antenna-LED, the accelerated spontaneous emission can compete successfully against III-V edge recombination. This surprising result raises possibility of making a practical antenna-LED using conventional III-V materials and processing methods. This is suggests that the antenna-LED might take its place among other important opto-electronic components needed for optical communications, sooner than would be the case if exotic new materials and processes would need to be developed.

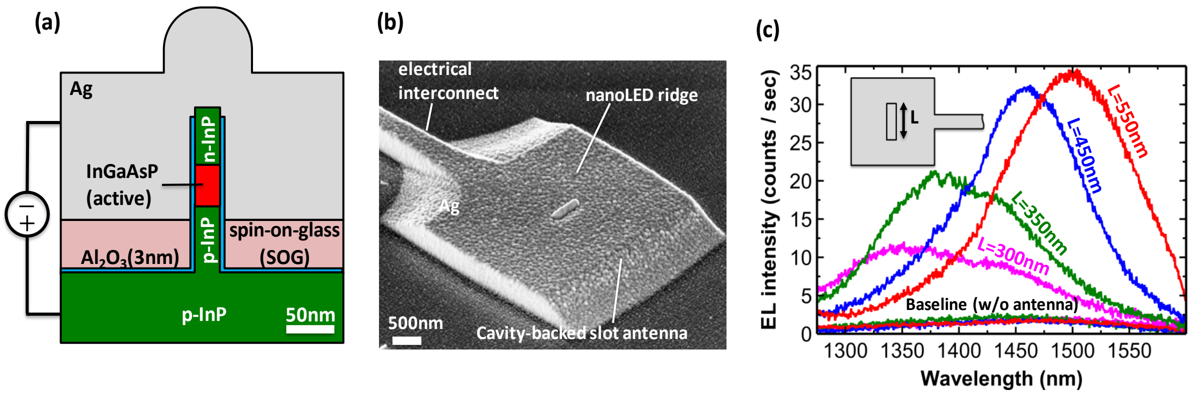


Figure 2.24. a) Cross-section schematic of electrically injected InP/InGaAsP nanoLED ridge coupled to cavity backed slot antenna. **b)** SEM image of fabricated nanoLED. **c)** Electroluminescence (EL) spectra from antenna-coupled nanoLED devices and baseline devices without antenna for several ridge lengths (L)field.

A new epitaxial wafer was designed by the **M. Wu** group at *Berkeley* and grown by the **Fitzgerald** group at *MIT*. InGaAs/InGaAsP LED structures were grown via MOCVD. This required calibrating InGaAsP quaternary alloys, and developing switching sequences to grow high-quality InGaAs-InGaAsP interfaces. Cross-section TEM imaging confirmed the InGaAs/InGaAsP multi-quantum well LED structure possesses good thickness control/uniformity and interface abruptness (Figure 2.25 left). Composition and strain state of the films was measured using high-resolution x-ray diffraction. A test LED built from the new wafer has 10x higher peak quantum efficiency compared with our previousy employed wafer purchased from external vendor. Furthermore, the new wafer reaches peak quantum efficiency at a significantly smaller current density suggesting that current injection efficiency is greatly improved compared with our previous wafers. Preliminary measurement of a nanoLED coupled to optical antenna using this new epitaxial material shows higher brightness with respected to previously fabricated antenna-LED's, which is an outstanding materials contributions by the **Fitzgerald** team.

The **Fitzgerald** group also grew samples with heavy Zn p-type doping in the active region. This heavy doping is predicted to enable faster spontaneous emission, which is needed to produce a sufficient number of photons/bit from such a small active region, without sacrificing efficiency. While Zn doping has been known to cause elevated inter-diffusion of fine heterostructures such as the multi-quantum wells discussed here, cross-sectional TEM imaging of the doped structures showed minimal inter-diffusion of the multi-quantum wells, as shown in Figure 2.25 (right).

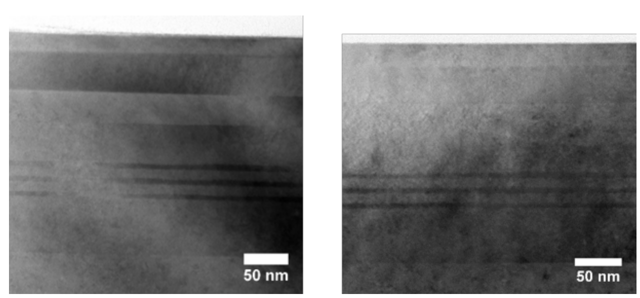


Figure 2.25. Cross-sectional TEM images of InGaAs/InGaAsP multi-quantum well LED structure (**left**) and heavy Zn p-type doped samples (**right**).

Members of the nanophoyonics theme have completed analysis of predicted direct modulation speed and spontaneous emission enhancement of optimized III-V antenna-LED [12]. It was found that >100 GHz direction modulation speed is possible with > 25% quantum efficiency by using a multiple quantum well (MQW) active region that is heavily doped p-type. At the same time, it is expected that >300 photons can be emitted per clock period, which is more than enough for projected photo-receiver sensitivity at the system level.

IIIb. Chalcogenide antenna-LEDs

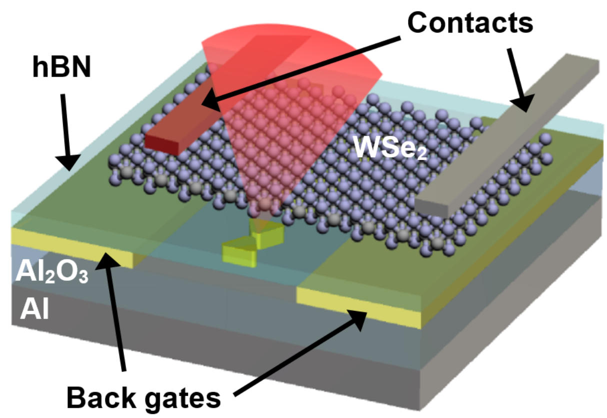


Figure 2.26. Schematic of electrically excited chalcogenide nanoLED design.

An alternative photo-transmitter material is represented by the new monolayer Chalcogenide semiconductors. This builds on the prior year research efforts in the **M. Wu** and **Yablonovitch** groups. Last year the first demonstration of optically pumped antenna enhanced spontaneous emission LED built from a transition metal dichalcogenide (TMDC) monolayer composed of WSe_2 was achieved. The chalcogenide monolayers are being explored for the possibility of diminished non-radiative edge recombination compared to the III-V materials. This project is in collaboration with the **Javey** group (*Berkeley*), taking advantage of their extensive expertise in 2D monolayer chalgcogenide materials. It should be emphasized that this inter-disciplinary collaboration is a hallmark of the Center for E^3S. In the current period, the chalcogenide nanoLED concept was extended to all-important electrical injection, and a functioning device has been simulated and demonstrated. While TMDCs offer the possibility of highly efficient nano-emitters due to low surface recombination rates, taking advantage of this in an electrical injected device involves careful consideration of the device design to limit edge recombination and to create some sort of carrier confinement that is required for high efficiency devices. Several different device/antenna configurations were designed and tested in this period.

Initial successful demonstration of light emission of from WSe_2 TMDC by electrical charge injection was achieved by the **Wu** group on a dual back gates device to form a PIN junction. A comparison of the electroluminescence properties of WSe_2 with photolu minescence is given in Figure 2.27. The evaluated emission quantum efficiency of electroluminescence in this device is around 50 times smaller than photolum-inescence.

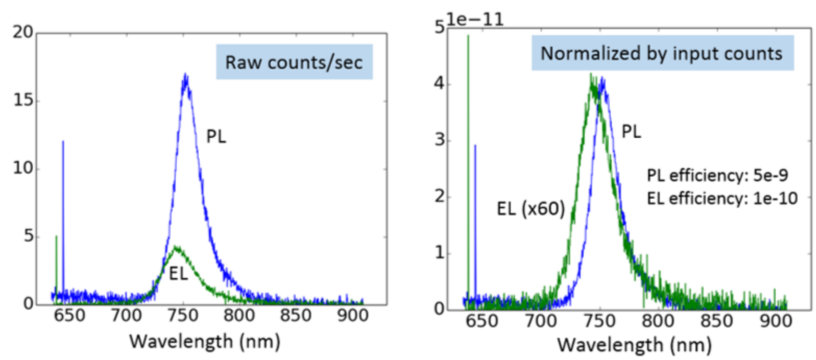


Figure 2.27. Left: Raw counts per second from electroluminescence (EL) and photoluminescence (PL) of WSe_2 monolayers. **Right:** Quantum efficiency obtained by dividing by input counts. Note, however, that the efficiency of the optical setup is not taken into account.

Improvements were also made to the measurement setup in collaboration with the **Yablonovitch** group. The improvements now allow for the measurement of scattering properties and photoluminescence emission from individual antennas. This greatly improves the ability to characterize devices and probe the different mechanisms for enhanced light emission. In particular, this setup now allows to distinguish from enhanced pumping and enhanced emission of our WSe_2 monolayers. Scattering measurements also enable to characterize antennas without the presence of an active material which greatly speeds up device prototyping.

On the fabrication end, the group demonstrated fabrication of high quality slot antennas using helium-ion milling [33]. Spontaneous emission enhancement up to ~37× from slots with 20-nm gaps were achieved, based on polarization ratio. Comparison with Ga-ion milling, which has a resolution limit of 35nm, has confirmed that correspondingly wider antennas have similar performance between the two fabrication techniques. Bowtie antennas were fabricated and, all-importantly, electrically injected devices have been demonstrated using WSe_2 (Figure 2.28) [34].

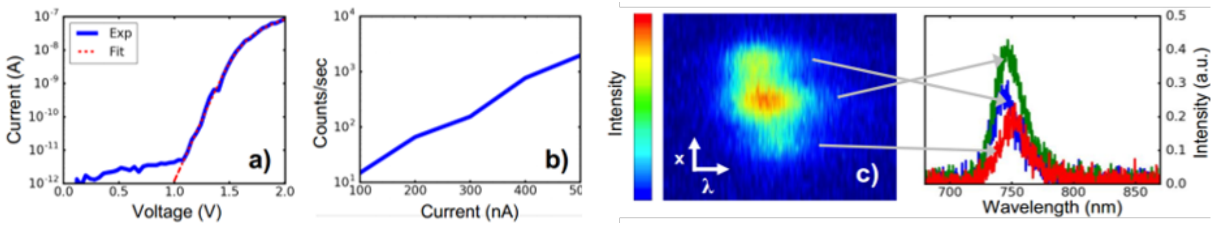


Figure 2.28. a) Current versus p-contact voltage, with fit to diode with series resistance. **b)** *L-I* curve of device. **c)** Spectrograph of light emission, with individual peaks plotted on the right.

In addition, a novel method of generating electroluminescence in WSe_2 monolayers has been discovered. By applying an AC voltage (kHz to MHz frequencies) to a back gated device, bright electroluminescence can be observed near the contact. The highest efficiency achieved for these devices is estimated at $\sim10^{-6}$, compared to $\sim10^{-9}$ for PIN diode devices. Capacitive coupling might provide a simpler fabrication route for testing optical antennas, and might actually be practical for a real optical communications link.

IIIc. First Principles Analysis of the Photo-Receiver as a Systems/Physics Problem:

From the beginning of the Center, the nanophotonics theme has recognized that a highly sensitive photo-receiver with a low capacitance as a key to reducing the energy consumption of the complete optical link. The reason is that low detector capacitance reduces both the photons/bit required from the transmitter side as well as providing larger receiver signal voltage, reducing amplifier energy consumption. Owing to the highly integrated nature of the Center for E^3S, with device researchers being guided by circuits and systems researchers, we have done a complete re-examination of the detector/pre-amplifier/bit comparator photo-receiver system.

In agreement with previous studies, E^3S nanophotonics researchers have found that the photodetector be of sufficient size to absorb the photons, while the nano-scopic, short-transit-time, high-speed amplifier pre-amplifier must be small, presenting mutually conflicting requirements. Thus the photo-transistor effort in the Center, which tried to combine both functions in a single device, has been eliminated. Nonetheless the detector and amplifier functions must be as tightly integrated as possible, to reduce the capacitance of the interconnect wire. At present, this strategy is not being pursued by the silicon photonics industry, since it would require new engineering costs associated with necessary process changes. For the goals of the E^3S Center, this approach will be essential in the future, since the antenna-LED is a nanoscopic device with a very small active region that is limited in the number of photons/bit that can be produced. Sensitivity, low noise, and high-speed are essential in the photo-receiver. Along these lines, we believe that it is time to provide optical cavity-enhancement to the photo-diode function.

After thus reducing device capacitance, the next important step has to do with the feedback resistor in the intial trans-impedance amplifier circuit, as shown in the RX Macro circuit given in Figure 2.29.

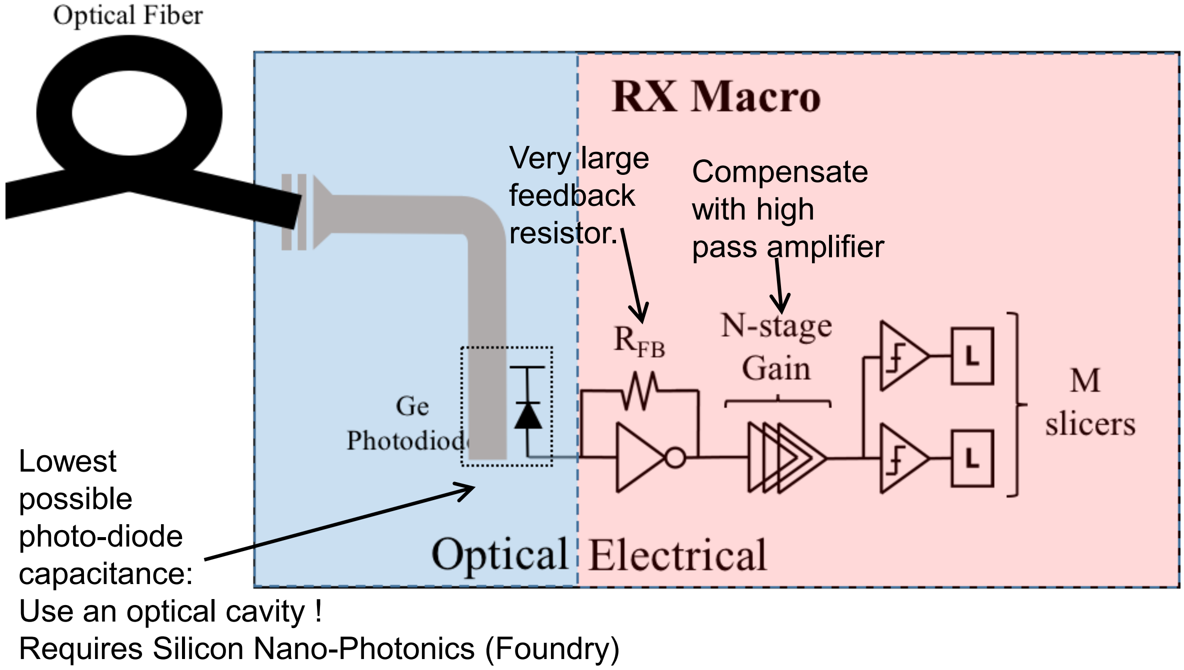


Figure 2.29. A block diagram showing some of the new features that will be needed to make a more sensitive photo-receiver; (1) cavity enhanced photo-diode; (2) A very large feedback resistor on the initial trans-impedance amplifier, compensated by high-pass frequency response in the succeeding amplifier stages; (3) multiple serial to parallel slicers that split the load on the parallel slow comparators (not shown) that decide whether the bit is a 1 or a 0.

In order to reduce Johnson Noise and to provide the highest sensitivity, it is best to use large feedback resistor R_{FB} in the trans-impedance amplifier. Such a large resistance would make the initial amplifier very slow. The solution is high-frequency pass compensation in the succeeding amplifier stage which restore a flat frequency response, as illustrated in Figure 2.30. After the frequency compensation, the next problem is that the comparator circuits that decide whether the digital signal is a 1 or a 0, tend to be rather slow, since they measure small differences which take time to build up. In current commercial systems excess optical power needs to be provided so that the comparator can keep up a respectable data rate. The solution is to use a serial to parallel splitter that would permit the comparators work in parallel, at their slower inherent speed. We have presented this parallel solution to the silicon photonics industry, and they seem poised to adopt this innovation, which would greatly improve their throughput and reduce their energy consumption. If this happens, then we will be able to regard this as an important success of the E^{3}S Center.

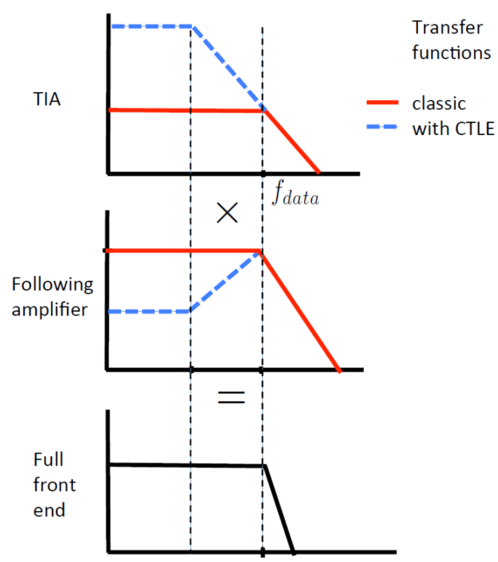


Figure 2.30. Compensate for slow feedback resistor with high pass amplifier in the Trans-Impedance-Amplifier TIA .

The three solutions from the caption to Figure 2.29 are combined in Figure 2.31, which illustrates the possible photo-receiver performance. The value of optical cavity enhanced photo-detection is indicated by the red cavity Q, with 150 < Q < 1000 represented the upper limit on needed cavity Q for high efficiency operation. V_{TX} is a measure of the efficiency of the photon source, with V_{TX}=1 corresponding to 100% light source efficiency. There is clearly a need to make the photo-diode smaller than 1μm. It appears unlikely that our strategy is sufficient to reach the quantum limit, 20 photons/bit, but it appears that two orders of magnitude improvement will be possible, relative to today's direct detection technology.

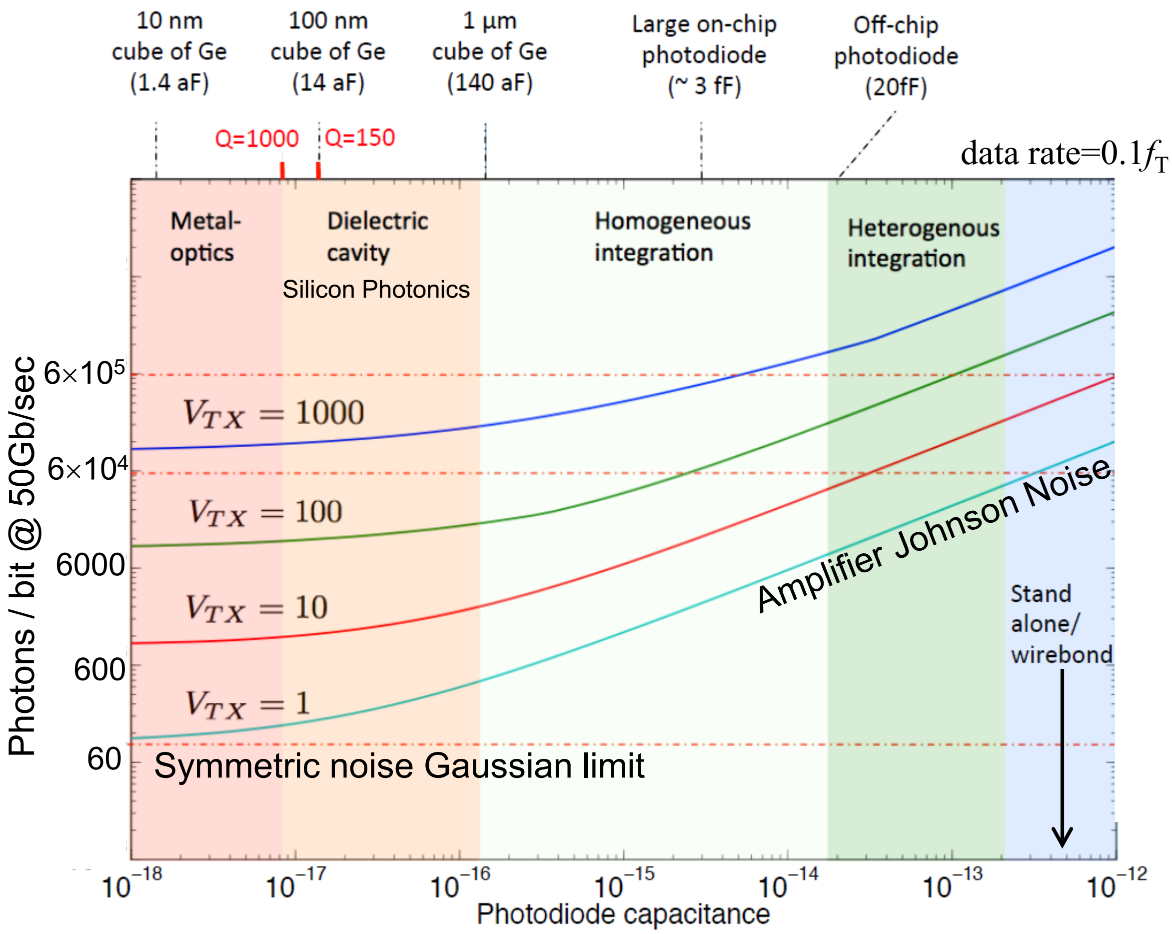


Figure 2.31. Optical Communications efficiency in photons/bit versus Photo-diode capacitance. Going down to <200 photons/bit appears possible, at high speed, using state-of-the art pre-amplifier transistors, with the photo-receiver improvements discussed in the caption of Figure 2.29, especially the optical cavity enhancement Q; 150 < Q < 1000. At the same time light source efficiency represented by V_{TX}~1must be maintained.

The nanomagnetics theme has continued pursuing its goal of achieving magnetic switching with ultra-low switching energies in the sub-femtojoules range and at high switching speeds below 10 picoseconds. In particular, the latter goal is a big challenge as spin states of magnets are very slow to switch. The focus of the nanomagnetics theme has been to understand the fundamental physics and the underlying switching dynamics of spintronic phenomena. In their research efforts, theme IV researchers are taking advantage of ultra-sensitive current driven switches employing actuated spin-orbit torque (spin-Hall effect) to switch a magnet, which in turn changes a voltage-biased magneto-resistor, producing output current [13]. Such a component can have current in/current out gain, as well as fanout. In general, nanomagnetics are attractive low-energy switching candidates since the constituents tend to be metallic. Thus, the voltage requirement is low, which is compatible with the goal of low dynamic power as the digital circuits switch. In addition, the non-volatility of magnets can be used to reduce the static power losses.

Despite these desirable properties of magnetics-based switching, device applications are currently hampered by the low speed of magnetic switching and the low On/Off ratio of state-of-the-art magneto-resistors. The nanomagnetics theme led by **Jeffrey Bokor** (*Berkeley*) has been addressing these issues and has made a significant breakthrough in magnetic switching speed by achieving sub-picosecond electric switching of magnetic materials (details are discussed below). Additional key achievements in this period include fabrication and characterization of square spin-transfer torque (STT) based magnetic tunneling junction (MTJ) devices in the size range below 10 nm. A significantly reduced switching current density and a substantially increased magnetoresistance value (above 100%) were observed. On the circuit level, non-volatile CMOS/spin-logic hybrids were designed with hybrid register and SRAM blocks. In this design, non-volatile spin-logic is used to add non-volatile function to CMOS registers and SRAM without compromising their native speed.

In the following, details are provided for the Period 7 nanomagnetics theme research efforts in:

IVa. Picosecond Magnetic Switching
IVb. Spin Hall Effect and Magnetic Tunneling Junction Devices
IVc. Computing using Magnetic Nonvolatile Devices

IVa. Picosecond Magnetic Switching

Last year (Period 6) the **Bokor** group reported helicity-independent optical pulse-induced ultrafast magnetic switching in the picosecond range in the ferrimagnet GdFeCo for laser pulse widths of around 55 fs. This work was based on previous reports of this effect [14], and while the mechanism for this phenomenon is still in debate, this process provided an interesting first step toward ultrafast magnetic switching. In the current reporting period, the **Bokor** group in collaboration with the **Salahuddin** group (*Berkeley*) demonstrated magnetic switching of the same ferrimagnet even when hit with laser pulses as long as 10 ps (Figure 2.32). The threshold laser fluence increased by only 50% as the pulse duration increased by over two orders of magnitude. The efficacy of longer pulses was a major step toward electrical pulse-induced magnetic switching: Whereas femtosecond electrical pulses are out of question, electrical pulses of around 10 picoseconds are within reach of conventional CMOS technology. In fact, conventional CMOS scaling is projected to reach transistor speeds in the range of a few picoseconds, opening up the possibility of on-chip ultrafast magnetic switching. The possibility of electrical

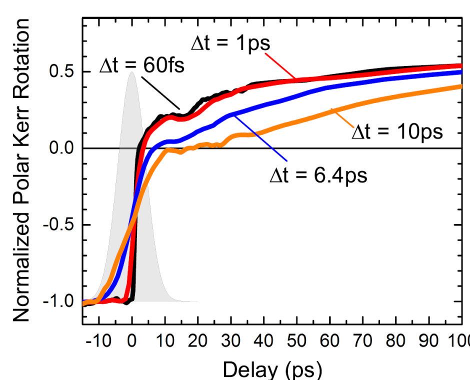


Figure 2.32. Magnetic switching behavior in GdFeCo as a function of pulse width of the laser inducing the electron heating.

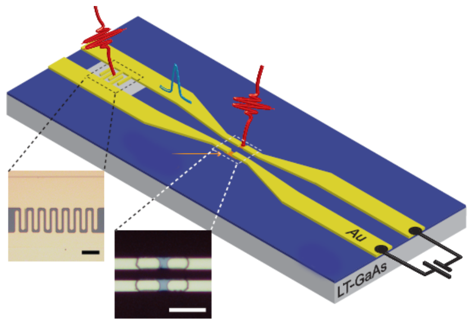


Figure 2.33. Ilustration of an ultrafast photoconducting switch (sometimes referred to as an "Auston switch".

switching of magnets was further strengthened by an experiment in which ultrafast, unpolarized electronic heat diffusion from a 55 fs laser-heated non-magnetic metal film adjacent to a GdFeCo film was observed to induce toggle switching in the magnetic GdFeCo layer [35]. This result proved that optical pulses are not needed to induce switching but the switching is induced by injection of hot electrons into the magnetic layer.

Motivated by these highly promising results, the **Bokor** and **Salahuddin** groups explored ways to generate picosecond electrical pulses. Making use of an ultrafast photoconducting switch (sometimes referred to as an "Auston switch"; Figure 2.33) they were able to launch 2-5 ps electrical current pulses on a microwave stripline. When this pulse was injected into a GdFeCo resistive load, indeed, ultrafast magnetic switching of the ferrimagnet GdFeCo was observed, as detected by time-resolved MOKE microscopy (Figure 2.34) [36].

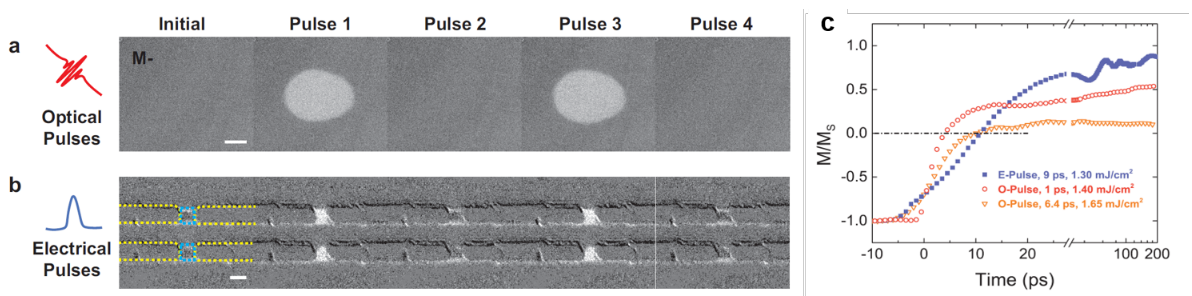


Figure 2.34. a) and **b)** Time-resolved MOKE micrographs of ultrafast (sub-10-picosecond) switching of ferrimagnetic GdFeCo switched by optical and electrical pulses. c) Magnetic switching behavior in GdFeCo as a function of pulse type and width.

This is a completely new mechanism of magnetic switching and opens the door to on-chip operation using conventional CMOS electrical pulses. To pursue this goal, a new collaboration has been initiated between the **Bokor** group and the group of **Philip Wong** at *Stanford*. This collaboration involves integrating magnetic device structures on advanced CMOS chips in order to test magnetic switching triggered by electrical pulses generated directly by CMOS circuits. This collaboration brings in the **Wong** group's expertise in integrating novel devices on top of CMOS and it would not have been possible without the Center because the two groups would not have become aware of each other's work and expertise otherwise. In addition, the Bokor and Salahuddin groups are exploring ways to extend ultrafast switching observed in ferrimagnetic GdFeCo to ferromagnetic materials. A promising step in this direction has been the observation of ultrafast, helicity independent, optical single-shot toggle switching of a thin CoPt ferromagnetic layer grown on a GdFeCo layer [37]. When this stack is irradiated by single 55 fs laser pulses, reliable toggle switching of the two coupled layers is observed. The ability to switch a ferromagnet by ultrafast excitation will greatly expands options for design of an integrated switching and readout device.

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

The **Salahuddin** group studied spin-orbit torque (SOT) switching of ferrimagnetic $Gd_x(Fe_{90}Co_{10})_{100-x}$ films, denoted as GFC, for both transition metal (TM)-rich and rare earth (RE)-rich configurations. One of the key metrics for SOT driven switching is to quantify how much torque is created on the magnet for a given amount of current. In a typical experimental structure a ferrimagnet is placed right on top of a metal with strong orbit coupling. In our case, this metal is Pt. As the current flows in Pt, it is converted into a spin current by the spin orbit coupling. The spin current, in turn, exerts a torque on the magnet. One way to quantify the efficiency of such torque is to express it in terms of a magnetic field. In other words, one measures what is the equivalent magnetic field that the magnet would fill when the spin current reaches it. Once such magnetic field can be extracted, the ratio of this 'apparent magnetic field' (B_{eff}) to the charge current density gives a measure of the torque efficiency. In this reporting period, the **Salahuddin** group performed systematic experiments with a large number of samples having different volume fraction of Gd. All samples were fabricated using ultra high vacuum sputtering and characterized by conventional magnetometry such as the vibrating sample method (VSM). Figure 2.35 (left) shows the variation of saturation magnetization M_s as a function of Gd concentration. As expected, the value of M_s drops around the compensation point for the magnetic moment. Figure 2.35 (right) gives the measured data for the torque efficiency (B_{eff}/J). It is interesting to note that the torque efficiency peaks right around the compensation point. While this is currently not well understood, the torque efficiency going up around the compensation point might indicate a non-trivial effect on the spin angular momentum of the two sub lattices since the torque is exerted through angular momentum transfer. Currently, theoretical work is underway to predict and explain this observation.

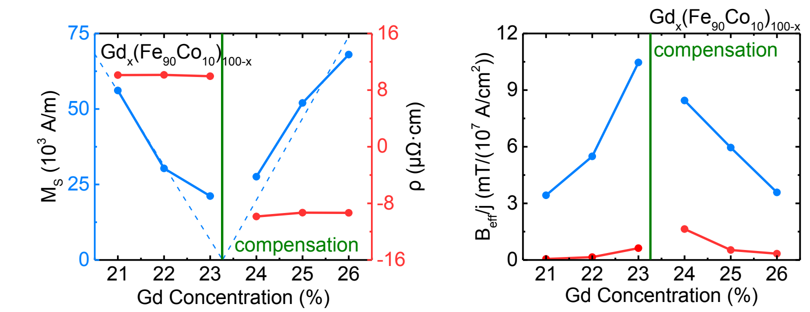


Figure 2.35. Left: Magnetometry results showing variation of saturation magnetization as a function of volume fraction of Gd. **Right:** Torque efficiency as a function of volume fraction of Gd. The torque efficiency is measured by second harmonic spin transport measurements.

The **Khizroev** group (*FIU*) strives to understand the new physics of spin-transfer torque (STT) magnetic tunneling junctions (MTJs) in the previously unexplored sub-10-nm size range and exploit the new physics to build next-generation devices with superior properties including low switching current, high magnetoresistance, and ultra-fast switching [38]. This work is based on ab initio theoretical calculations, which have predicted that at device size ranges below 5 nm, the surface-to-volume contribution to the spin effect is drastically different from that in the traditional size effect above 10 nm. The experimental approach pursued by the Khizroev group uses a nanoparticle-based device structure. The nanoparticles are made of the high-anisotropy ferrimagnetic material CoFe2O4 while the magnetic layers are made of traditional high-anisotropy CoFeB compositions used in STT junctions (Figure 2.36 left). A high-resolution TEM image of a 2-nm nanoparticle is shown in Figure 2.36 (right). The nanoparticles are separated from the two magnetic layers by a thin layer of MgO (~0.3 nm). The measured I-V curves confirmed the single-electron behavior of such junctions; a characteristic Coulomb stair could be observed, as shown in Figure 2.37 (left). The stair corners are shown by black arrows. Typical room-temperature low-field magnetoresistance (MR) curves for the junction are shown in Figure 2.37 (right). The room-temperature MR curves show sharp peaks with a magnetoresistance value above 100%. The curves

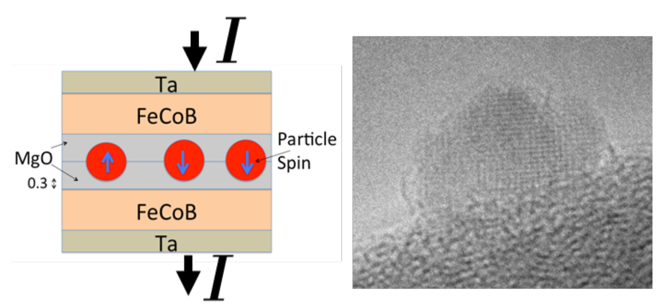


Figure 2.36. Left: A MTJ structure with $CoFe_2O_4$ nanoparticles sandwiched between two magnetic layers. **Right:** A high-resolution TEM image of a 2-nm $CoFe_2O_4$ nanoparticle.

were measured at a current of approximately 50 nA. This is a significant result which shows that indeed the spin physics in such small nanoparticles could be used to significantly increase the magnetoresistance value in next-generation spintronic devices. Moreover, the Khizroev group's theoretical predictions (using a trivial model of field-dependent Landau energy levels) for the room-temperature MR value are above 10^5—provided that nanoparticle size can be further reduced.

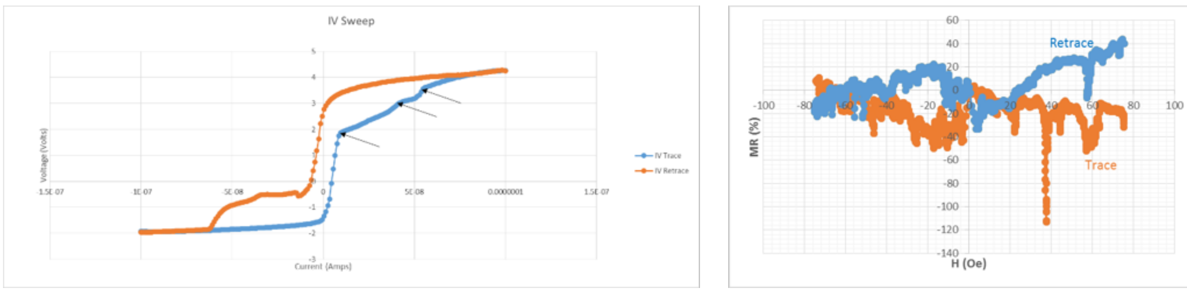


Figure 2.37. Left: A typical *I-V* curve for a MTJ device with nanoparticles sandwiched between two magnetic layers. **Right:** Typical low-field magnetoresistance (MR) curves showing the dependence of the resistance of the nanoparticle-sandwiched junction on the magnetic field.

IVc. Computing using Magnetic Nonvolatile Devices

This project, which was started in the previous period by the **Stojanovic** and **Bokor** groups (both *Berkeley*) [39] has significantly expanded in this period by the **Wong** group (*Stanford*) joining the team. The project focuses on the fabrication, design, and integration of in-memory and normally-off computing using magnetic nonvolatile devices. One impactful way to reduce the power consumption of computers is to turn off large portions of the computer that are not in use. The use of nonvolatile memory can make normally-off computing viable, since the shut-down part of the computer can be restored to its original state once it is needed, without needing to write to or read from external storage. Additional power savings are possible by distributing the memory over the circuit (memory-in-logic, mLogic), due to reduced interconnect length [40]. The **Stojanovic** group analyzed the mLogic circuit and also the more general transpinor-based logic efficiency and optimization (Figure 2.38 top). Furthermore, new ways to improve the energy at the circuit level were investigated, such as capacitively-coupled spin-logic (CC spin-switch) shown in Figure 2.38 (bottom) and hybrid spin-CMOS logic for nonvolatile D flip-flop and SRAM cells.

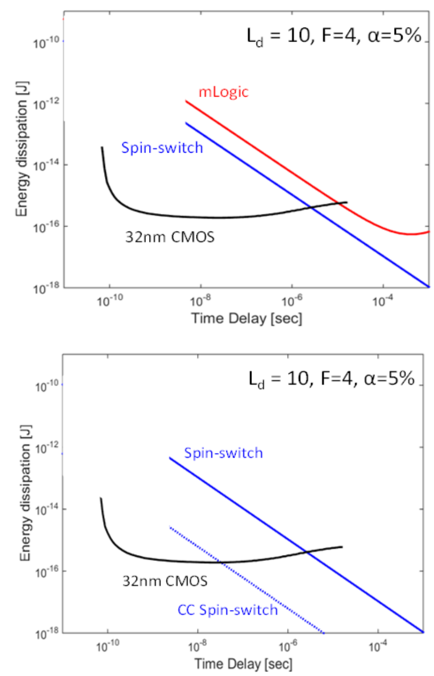


Figure 2.38. Circuit analysis and comparison to CMOS for mLogic (top) and CC spin switch (bottom) circuits.

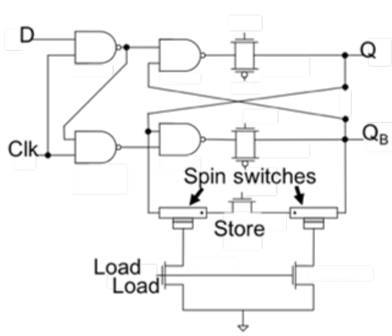


Figure 2.39. Circuit diagram for latch to use nonvolatility of spin switches. The Store transistor allows to store Q into the two spin switches; the Load transistors allow to reload Q from the spin switches back to the circuit.

Experimental efforts for integrating spin Hall devices with FETs to build SRAM and flip-flops, and to show that the circuits are nonvolatile and have no impact on circuit area, were led by the **Wong** group. Significant progress has been made in the fabrication of the example circuit and the fabrication of the spin switches. The final step will be integration of the two. The nonvolatile latch circuit the group is building is a CMOS latch with an input D, clock Clk, and outputs Q and Q_B (Figure 2.39). Two spin switches with oppositely magnetized wires are attached to the latch. The "store transistor" stores Q into the magnetization of the spin switch, and the "load transistors" reloads Q into the circuit. The first key outcome in this period was completion of a tapeout of the latch using 130 nm CMOS and V_{dd} = 1.8 V. For this, a SPICE model of the CMOS-magnetic hybrid circuit was built that included the physical behavior of the magnetic devices. The design parameters were optimized for maximum current to drive the spin switches, which resulted in a requirement that the spin switch wire width be under 300 nm. The model also predicts that spin switches with tunnel magnetoresistance > 15% are needed to successfully restore the latch circuit. The tunnel magnetoresistance is defined as TMR = 100 x ($R_{AP} - R_P$)/R_P, where R_{AP} and R_P are the device resistances when the two magnetic layers have antiparallel and parallel magnetization, respectively. An example transient, which successfully stores and loads the state of the latch from the spin switches is given in Figure 2.40.

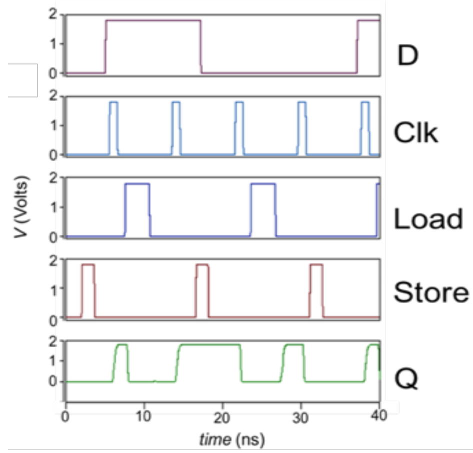


Figure 2.40. SPICE transient output for hybrid CMOS-magnetic circuit showing correct Store and Load operation for 130 nm tapeout with optimized CMOS and magnetic devices.

The second key outcome in this period was full fabrication of the spin switch in collaboration of the **Wong** and **Salahuddin** groups. It consists of a magnetic wire with a tunnel junction in the center, as shown in Figure 2.41 (left). The team chose to switch the memory devices using the spin Hall effect, which is about 100x more energy efficient than more traditional spin torque transfer. Thus, thin film stacks were grown by sputter deposition and UHV annealing and optimized to have perpendicular magnetic anisotropy, which is also desirable for more energy-efficient switching. The magnetic wire could be switched using the spin Hall effect down to 150 nm wide wires, within the design parameters of our SPICE circuit. In larger, 20 µm wide, wires the switching current density was found to be $J_c = 0.8 \times 10^{11}$ A/m^2, and it increased slightly in the 150 nm scaled wires to 1.4×10^{11} A/m^2, most likely due to increased edge roughness influence and different magnetic switching dynamics. It should be emphasized that this is about 10-times lower switching current density than spin transfer torque switching, e.g. [41]. Finally, the **Wong** and **Salahuddin** groups developed and carried out full fabrication of the device with the tunnel junction in the center of the wire. The process uses electron-beam lithography and includes five lithography steps and three etch steps using tools at *Stanford* and *Berkeley*. Initially, field-induced switching of the spin Hall device with TMR = 7% was demonstrated. Since then, the group started a collaboration with the Center's industrial research partner Applied Materials to use their

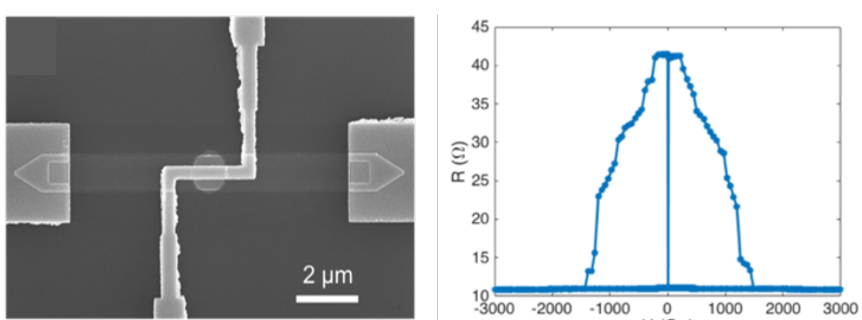


Figure 2.41. Left: SEM image of fabricated 3-terminal spin switch with tunnel junction in the center. **Right:** Resistance of the device vs. out-of-plane applied magnetic field, showing perpendicular magnetic anisotropy and 285% TMR.

highly optimized thin film growth. Samples from Applied Materials displayed TMR = 285% and were patterned as shown in Figure 2.41 (right). Even accounting for current-crowding, this is one of the highest TMR reported. The switching of the free magnetic layer occurs around 5 Oe and the fixed layer switches around 1500 Oe. While this collaboration with one of the E3S industrial research partners is an excellent example of the importance of having a Center structure, the Wong and Salahuddin groups will continue to improve their own film growth and TMR values by exploring different materials for the pinned layer of the MTJ to try to increase separation between the free layer and pinned layer switching. In addition, improvements of the annealing conditions are underway to prevent oxidation of the MgO tunnel barrier during the annealing step.

2b. Table 2.3. Performance Against Metrics

Metric		P2	P3	P4	P5	P6	P7
Multi-PI projects	*Targets*	30%	not defined	not defined	75%	**50%**	**60%**
	Results	**44%**	**67% (14)**	**55% (12)**	**64% (14)**	**65% (11)**	**79% (15)**
Multi-Institutional projects	*Targets*	30%	not defined	not defined	30%	**15%**	**20%**
	Results	**4%**	**10% (2)**	**9% (2)**	**23% (5)**	**29% (5)**	**32% (6)**
Publications with authors from multiple institutions	*Targets*	12	3	5	5	**5**	**5**
	Results	**0**	**1**	**1**	**1**	**3**	**4**
New joint research funding awards	*Targets*	*(new for P6-10)*				**1**	**0**
	Results					**0**	**3**

The Center for E^3S continues to be a highly collaborative environment for faculty, postdocs and student researchers. This collaborative spirit is also exemplified by the high number of both multi-PI and multi-institutional projects—both exceeding the target numbers set in the Center's Strategic Plan. This highly collaborative environment has also translated into co-authorship in journal publications and conference proceedings. So far, the Center published 41 journal articles in this reporting period, 41 percent of these publications have two or more faculty co-authors. An area of concerns in the Center have been that the large number of multi-institutional projects (32 percent) has not been reflected in the number of joint multi-institutional journal publications (10 percent). While there is an upward trend in recent years, the Center leadership has taken steps to further improve these numbers.

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

2c. Research in Period 8

No major changes in the research directions of the four themes and system integration are planned in Period 8. The research will be guided by the Strategic Research Plan that is given in the Context Statement. The only change in faculty participation will be that **Dimitri Antoniadis** (*MIT*) will phase out of the Center within the first few months of Period 8. This decision was made between Prof. Antoniadis and the Center leadership as a result of the emphasis of the nanoelectronics research focus from traditional III-V semiconductors to new types of semiconductors, such as two-dimensional transition metal dichalcogenides (2D-TMDCs) and graphene nanoribbons (GNRs). This transition in research strategy in the nanoelectronics theme has been in progress during the last two periods and came to full fruition in this funding period with the addition of Profs. **Jing Kong** (*MIT*) and **Steven Louie** (*Berkeley*) The following faculty participation table is to serve as a guide for the following narratives on the research plans in Period 8. It should be pointed out that all four research themes continue to have multi-institutional participation.

Faculty Participation by Theme in Period 7

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

Legend: x* denotes Theme Leader; x denotes phasing out of the Center

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

The nanoelectronics research efforts led by theme leader **Eli Yablonovitch** (*Berkeley*) will continue to investigate band-to-band tunneling at low turn-on voltage in traditional semiconductors as well as exploring tunnel devices based on new two-dimensional semiconductors. Research on traditional semiconductors will be aimed at understanding of the role of interfacial traps as detractors to band-to-ban tunneling, and will be conducted mainly in the **del Alamo** group (*MIT*) and the **Yablonovitch** group. Research toward new low-defect density semiconductors will continue to focus on (1) optimization of transition metal dichalcogenide TFETs by the **Javey** and **Yablonovitch** groups (both *Berkeley*) and the **Kong** group (*MIT*), and (2) bottom-up synthesis, assembly and characterization of graphene nanoribbon based tunneling devices. The latter efforts will be led by the **Fischer** group (*Berkeley*) in collaboration with the **Swager** group (*MIT*), and will be guided by theoretical studies by the **Louie** and **Yablonovitch** groups (both *Berkeley*).

A more detailed description of Period 8 nanoelectronics research plans is given below.

- *III-V Nanowire TFETs:* The goal of **del Alamo** group (*MIT*) in Period 8 is to fabricate ~10 nm diameter InGaAs vertical nanowire transistors. This goal is based on recent progress in the development of etching technology based on RIE and digital etch that solved the past mechanical stability issue of sub-10 nm diameter III-V nanowires with high aspect ratio and smooth sidewalls. Furthermore, forming gas annealing will be used to improve the interfacial quality of nanowire transistors and the contact resistance. In more detail, the **del Alamo** group aims to improve the isolation characteristics of their process. That is isolation of the gate to the bottom contact and to the top contact. In addition, efforts will be aimed at optimizing the contact characteristics at the top, which, at the moment, is the major current bottleneck of these transistors. With all this in place, the group will fabricate ~10 nm diameter VNW MOSFETs, TFETs and superlattice-source FETs. All transistors will be thoroughly characterized over a broad temperature range and the band-edge sharpness around the energy gaps will be extracted.

  In collaboration with the **Yablonovitch** group (*Berkeley*), the **del Alamo** group will also develop a 3D simulation environment that solves electrostatics and quantum confinement effects self-consistently to help explain experimental characteristics of nanowire TFETs and MOSFETs and design new device structures. In addition, the **Yablonovitch** group will further investigate the impact ionization mechanism, and how desired band-to-band tunneling can be increased without increasing undesired impact ionization leakage.

- *Chalcogenide TFETs:* The **Javey** group will continue its successful superacid treatment methods of 2D transition metal dichalcogenide (TMDC) semiconductors to heal defects that would be detrimental to performance of devices like TFETs which require sharp band edges and defect-free interfaces. A particular goal of Period 8 will be to extend the superacid treatment to heal defects of chemical vapor deposition (CVD) grown TMDCs and subsequently demonstrate high performance 2D-2D tunneling field effect transistors. The TFETs demonstrated previously were fabricated using tape-exfoliated TMDCs. With the use of CVD grown TMDC flakes in collaboration with the **Kong** group (*MIT*), large area devices can be fabricated. At the same time, superacid will be used to passivate defects in the 2D layers, thereby improving the heterojunction interface and enabling steep turn-on of TFETs. Device analysis and optimization will be performed, including doping of contacts.

  The **Kong** group will also explore MOCVD growth of high-quality TMDC materials and, in collaboration with the **Javey** group, compare results to CVD and exfoliated TMDCs. In addition, the **Kong** group will develop characterization techniques to reveal the various type of defects in TMDC materials and their density. Methods will include scanning transmission electron microscopy to directly "see" various types of defects and photoluminescence mapping with scanning near field optical microscopy (SNOM) to characterize defects. Various scanning probe microscopy methods will also be applied, such as scanning gate microscopy, scanning conductance microscopy to characterize our samples. Characterization results will be analyzed in collaboration with the **Yablonovitch** group with respect to bandgap defect state densities, D_{it}. Results will then be fed back into the synthesis loops to adjust growth conditions by both the **Kong** and the **Javey** group for improving the quality of the TMDC materials.

- *Graphene Nanoribbon TFETs:* The goal of this research program in Period 8 will remain to optimize the rational bottom-up strategy developed in the **Fischer** group—with theory guidance by the **Louie** and **Yablonovitch** groups (both Berkeley)—towards integrating a molecularly defined quantum tunneling junction into a single graphene nanoribbon (GNR). To this end, model Hamiltonian, first-principles methods, and Green's function techniques will be used by the **Louie** group to characterize the electronic, transport, and optical properties of conceived devices. Specifically, new geometric and doping configurations of GNRs for practical device application will be studied, as well as novel device design for minimization of energy consumption. These studies will use setups such as double resonance quantum wells to break the Boltzmann limit of swing voltage and reach milli-Volt conductance switching, which could function properly even at room temperature. In addition, efforts will be directed to find a synthesizable metallic graphene nanoribbon structure as transistor leads.

Based on theoretical results the **Fischer** group has identified key structural targets required for the assembly of a molecular quantum tunneling junction. In addition, molecular building blocks will be designed to yield GNRs featuring a metallic band structure. These metallic GNRs will serve as the conductive leads on either side of the quantum dot heterostructure. Furthermore, it is expected that metallic GNRs will significantly reduce the contact resistance between the GNR based device and the macroscopic metal contacts. With respect to the quantum dot tunneling junction, preliminary calculations indicate that an alternating semiconducting GNR heterostructure comprised of short segments of undoped and B-doped GNRs yields a band alignment reminiscent of a quantum tunneling junction. While the length of the pristine undoped segments (2-3 nm) determines the width of the tunneling barrier, a short segment (4-6 nm) of B-doped GNRs serves as the QD. We will target the assembly of this segmented GNR heterostructure both on surface as well as in solution in collaboration with the **Swager** group.

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

Nanomechanics researchers led by theme leader **Tsu-Jae King Liu** (*Berkeley*) will continue their efforts toward the theme's goal of demonstrating reliable nano-electromechanical (NEM) switch (or relay) operation at or below 10 mV. The three main research topics of Period 7 will also continue in Period 8: 1) Design and fabrication of body-biased NEM relays led by the **King Liu** group in collaboration with the **J. Wu** and the **Stojanovic** groups (both *Berkeley*). 2) Reproducible fabrication of Squitch devices with reduced operating voltage by the *MIT* **Squitch** team of the **Lang**, **Bulovic** and **Swager** groups. 3) Optimization of the Stritch device design and characterization of switching properties led by the **Zubia** group (*UTEP*) in collaboration with the **King Liu** and **Javey** groups (both *Berkeley*).

A more detailed description of Period 8 nanomechanics research plans is given below.

- *Low-Voltage Relay Design:* During Period 7 the **King Liu** group in collaboration with the **J. Wu** group successfully demonstrated stable sub-50 mV relay operation, by designing the relay for non-pull-in-mode operation to minimize the hysteresis voltage and by coating the relay with a molecular layer to reduce contact adhesive force. Period 8 work will be devoted to optimize the molecular material to achieve steeper effective subthreshold swing without increasing the contact adhesive force and thus, to enable operation with even lower voltage swing. The **King Liu** group discovered that contact resistance (R_{ON}) is higher for very low (sub-100 mV) voltage operation. This may be due to lower contact force (resulting in less intimate contact) and/or lower current flow in the ON state (so that any native oxide formed on the metallic contacting surfaces is not broken down), and is undesirable. A systematic study of R_{ON} and device endurance (number of switching cycles before failure) will be conducted to investigate the effects of the gate, body and source-drain operating voltages on relay reliability.

  The performance and reliability of relays with molecular coatings will also be systematically characterized. For this, the **J. Wu** and **King Liu** groups will join forces with the **Louie** theory group to develop a comprehensive understanding of the adhesion physics between solid surfaces and ways to alleviate it. The goal is to have a model that predicts the molecular coatings being able to optimally reduce adhesion while retaining a good ON-state electrical conduction between two electrode surfaces. The theory will be used to guide experiments to develop coating processes that will lead to reduced NEM switching voltage. The ultimate goal of this project remains the demonstration of reliable relay operation below 10 mV.

- *Squitch Project:* The Squitch team comprised of the **Bulovic**, **Lang** and **Swager** groups at *MIT* will continue its development of the squitch concept, a nano-electromechanical (NEM) switch designed to conduct *via* tunneling through an electromechanically compressed gap filled with a molecular monolayer. The focus of this work in Period 8 is expected to transition from fabrication process development to device development through optimized design, fabrication and testing. The primary development objective will be to lower the actuation voltage of the squitch. This will be accomplished by combining several activities. First, candidate molecular monolayers and/or composite layers will be proposed and synthesized. These monolayers will be designed to enable lowering of the actuation voltage. Second, the squitch will be used as an *in situ* metrology tool to characterize the electrical tunneling and mechanical behavior of candidate molecular layers. Third, with the metrology data in hand, a model-based optimization of the squitch to produce designs with lower actuation voltage will be carried out. The optimized designs will be fabricated and characterized, and the process will be iterated. Finally, in collaboration with the **King Liu** group at *Berkeley* a plan is in place to transition to more extensive use and testing of three-terminal squitches over two-terminal squitches.

- Stritch Project: Project leader **David Zubia** (*UTEP*) will continue to work closely with the **King Liu**, **Javey**, and **J. Wu** groups at *Berkeley* to study fundamental electrical-mechanical behavior of the stritch device while mitigating device fabrication issues. Proof-of-concept of the stritch device was established Period 7 using MEMS cantilevers that were not specifically designed for the stritch device. While strain-induced electrical and optical modulation was observed, the non-linear actuation of the cantilever and the mismatch in the size of the transition metal dichalcogenide (TMDC) semiconductor flakes (larger) with respect to the MEMS pads (smaller) created issues which limited testing due to premature device failure and low processing yield. Two failures modes are believed to be detachment of TMDC flakes from the MEMS and possibly TMDC rupture during high stress. In period, the use of MEMS chevron actuators is planned to match the size of the TMDC flakes to the pads and improve control of strain. The two failure modes mentioned above are attributed to the low deformation potential in the TMDCs, which, in turn, require high strain (~6%) to achieve sufficient ON/OFF resistance modulation (10^6). To address these electrical-mechanical challenges, the plan is to make an array of small holes in the TMDC layers. The holes will serve to dramatically concentrate strain around them while maintaining a relatively low global stress. If the array of holes is designed correctly, a highly conductive percolated path will occur allowing high ON/OFF ratios at lower global strain compared to hole-free membranes. The holes will also improve mechanical attachment and electrical contact of the TMDCs to the MEMS pads as gold will be deposited through the holes to serve as mechanical anchors and electrical contacts. It is expected that these device developments will lower voltage operation, increase ON/OFF ratio, improve device reliability, and increase process yield.

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

Ming C. Wu, nanophotonics theme leader, will continue to direct theme III researchers to make progress toward on-chip few-photon optical communication between electronic switches at unprecedented efficiency levels. The goal remains to experimentally reach several orders of reduction of photons-per-bit in a data-link from the current 20,000 photons/bit level. This goal of the **M. Wu**, **Yablonovitch**, **Chang-Hasnain** (all *Berkeley*) and the **Fitzgerald** group (*MIT*) will be pursued by further improving the antennaLED (both the III-V and chalcogenide approaches) and analysis/optimization of the photoreceiver integration at the systems level (**Stojanovic**, **M. Wu**, **Yablonovitch** groups; all *Berkeley*).

A more detailed description of Period 8 nanophotonics research plans is given below.

- *Antenna-Enhanced III-V nanoLEDs:* Based on the significant progress made in demonstrating a large increase in the spontaneous emission rate in III-V nanoLEDs by coupling to optical antennas, the **M.**

Wu and **Yablonovitch** groups plan to further refine this design in Period 8 in order to improve the efficiency of the device. Improving the efficiency is important from a practical standpoint but will also allow to perform time-resolved measurements of the light emission from the devices. The **Chang-Hasnain** group will contribute toward this goal by developing a method for an ultrathin layer of InP over-growth on the nano-patch to reduce surface recombination. Toward the end of the research period the team expects to be in the position to demonstrate time-resolved photoluminescence and time-resolved electroluminescence from the III-V antenna-enhanced nanoLED devices (with the **Chang-Hasnain** group). Plans are also underway to work toward integrating the nanoLED device on-chip with a waveguide. Previously, electrically injected nanoLED devices have been only coupled to free space; however, it is more desirable to couple the nanoLED to waveguide for integrated circuit applications. The goal is to achieve greater than 90% coupling to waveguide and first experimental results are expected during this Period 8.

The **Fitzgerald** group will continue to work on epitaxial challenges related to fabrication of low-energy antenna-enhanced LEDs. Heavy p-type doping in the active region is predicted to greatly speed up radiative recombination and therefore device speed without reducing efficiency. This effect is expected to be optimal at a doping of about 1×10^{19} cm^{-3}. Currently, the **Fitzgerald** group is only able to grow InGaAsP/InGaAs multi-quantum well structures with p-type doping of 5×10^{18} cm-3. Options for achieving higher doping in these structures will be pursued while still maintaining good interface quality and limiting interdiffusion of active layers caused by heavy Zn doping. This will include investigating different growth conditions such as temperature and V/III ratio, as well as using C as a dopant instead of Zn. In addition, growth optimization of InGaAsP/InGaAs multi-quantum well LED structures integrated with an InP waveguide structure will be pursued. This will be a first step towards demonstrating a full optical link including an LED, waveguide, and detector.

- *Chalcogenide Antenna-LEDs:* The **M. Wu**, **Yablonovitch** and **Javey** groups (all *Berkeley*) will continue to team up for this project. Building on the first demonstration of electrically injected devices with transition metal dichalcogenide (TMDC) semiconductors, in Period 8, the team will focus on quantifying and improving emission rate enhancement from antenna-coupled devices. TMDCs offer the possibility of highly efficient nano-emitters, un-inhibited by large surface recombination rates. Taking advantage of this in an electrical injected device involves careful design to limit edge recombination and to create some sort of carrier confinement that is required for high efficiency devices. In detail, the chalcogenide antenna-LED group plans to demonstrate >100-fold antenna enhancement in an electrically injected TMDC device, understand the mechanism of electroluminescence in AC-gated devices, and perform time-resolved measurements of photoluminescence to determine recombination coefficients and the antenna's effect on exciton lifetime.

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

The nanomagnetics theme led by **Jeffrey Bokor** will continue research toward achieving an ultra-low energy magnetic switch operating at speeds of a few picoseconds. Electrical charge-induced picosecond magnetic switching will be further optimized by the **Bokor** and **Salahuddin** groups (both *Berkeley*) and in collaboration with the **Wong** group (*Stanford*), ultrafast magnetic switching using electrical pulses generated on-chip in CMOS circuits will be pursued. The underlying nature of spin torque transfer and nanometer-sized magnetic tunneling junction devices will be studied by the **Salahuddin** and **Khizroev** (*FIU*) groups, respectively, whereas the **Wong**, **Bokor** and **Stojanovic** (*Berkeley*) groups will continue to pursue computing using nonvolatile magnetic devices.

A more detailed description of Period 8 nanomagnetics research plans is given below.

- *Picosecond Magnetic Switching:* In Period 8, a major goal for the **Bokor** and **Salahuddin** groups will be to further investigate the details of the physics of electrical current switching. Approaches for reducing the peak current and total energy required for electrical switching will be explored. The dependence of switching energy on the dimensions of the magnetic layer will be investigated. Optimal impedance matching will also be studied. Finally, multi-layered magnetic heterostructures will be studied to determine whether spin injection combined with electronic heating can lower the switching current threshold. In collaboration with the **Wong** group, this team will also build integrated CMOS and magnetic device circuits to demonstrate ultrafast magnetic switching using electrical pulses generated on-chip in CMOS circuits. A suitable electrical readout will later be integrated into the magnetic device. Non-volatile CMOS circuits will also be designed that embed magnetic devices in them so that they retain state with the power switched off. Furthermore, ultrafast optical "demagnetization" of the spin accumulation at nonmagnetic heavy metal surfaces will be studied in order to measure the time dynamics of spin-Hall effect. This will provide insight into the potential of ultrafast spin-Hall effect as a means for achieving picosecond switching in magnetic devices.

- *Spin Hall Effect and Magnetic Tunneling Junction Devices:* With the important observation of the increased torque efficiency at the compensation point in the current period, in Period 8, the **Salahuddin** group will focus on understanding the nature of spin torque transfer around this point. For this, the dependence of torque efficiency on thickness of the GdFeCo films will be investigated to provide an understanding of the scaling of the torque, which, in turn, should provide critical insight into the physics of torque transfer. The **Salahuddin** group will also study the influence of domain wall by directly imaging them while switching. In addition, time dependent measurements are planned, which could also reveal key information about the torque transfer.

  The **Khizroev** group will continue to exploit the new physics in magnetic tunneling junction devices with planar sizes in the sub-5-nm range in which surface effects dominate over volume effects. Thus, collective spin effects play a key role in this size range and determine the energy needed to switch spin states and enable extremely large ON/OFF ratios due to a significantly improved spin filtering in such a small size range. In addition to using a new three-beam focused ion beam (FIB) system, including high resolution helium and hydrogen sources, the Khizroev group will focus on novel approaches which use nanoparticles. For this, both magnetic and magnetoelectric (ME) nanoparticles with a diameter ranging from 10 nm to below 1 nm will be synthesized, and with different shapes and symmetries, including spherical, rectangular, and pyramidal nanoparticles.

- *Computing using Magnetic Nonvolatile Devices:* During Period 7, the **Wong** and **Stojanovic** groups in collaboration with the **Bokor** group accomplished the first two main goals of this project: circuit design/tapeout and spin switch device fabrication. Research efforts in Period 8 will focus on completing the third main goal of this project, which is full integration of the CMOS and spin switches and testing of the final circuit. The team also plans to conduct simulations and experimental realization of integration of the spin switches with 2D FETs to extend this project to not only using technologies that can be 3D monolithically integrated. In more detail, in Period 8, integration of magnetic devices in 3D monolithic fashion on top of CMOS is planned, as well as testing nonvolatility of the latch. Integration with 2D FETs for emerging-technology-only circuits will be pursued, starting with demonstration of integration of one magnetic device and 2D FETs before moving to full nonvolatile circuit. Throughout, simulations and modeling will be used to quantify the benefits of normally-off computing.

III. EDUCATION

1a. Goals and Objectives

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

The 2016 E^3S Annual Retreat included a breakout session on Education and Legacy. Led by **Tsu-Jae King Liu**, Associate Education Director, and **Lea Marlor**, Education Manager, the Center members reaffirmed the Education strategy that builds on the development of a pipeline of undergraduates who will be interested in research and graduate education. Developing online training materials on the Center's research will be emphasized in the Center's second five years and will serve as the venue to establishing the Center's Education legacy.

1b. Performance Metrics

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

Table 3.1.

Objective	Metrics	Frequency	Targets
Education	Center graduates completed E^3S training	Yearly beginning in Period 3	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50% Period 6: 15% Period 7: 30%
	Students and postdocs participating in education and diversity programs *(discontinued in the 2nd five years)*		
	Students accessing online courses of the Center *(new)*	Yearly beginning in Period 6	Period 6: 50 Period 7: 75
	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%
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Yearly beginning in Period 3	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80% Period 6: 85% Period 7: 85%

	Pre-college students who pursue a bachelor's degree in science and engineering	Yearly beginning in Period 3	Period 3: Baseline Period 4: 70% Period 5: 70% Period 6: 80% Period 7: 80%
	Students and postdocs serving in leadership roles in the Center	Yearly beginning in Period 2	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Period 6: 30% Period 7: 30%

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 has been dropped, given that the participation is organized under the E^3S Leadership Program.

1c. Problems Encountered

In December 2015, the E^3S Diversity Director, **Aimee Tabor**, unexpectedly passed away, shortly after joining the Center. At the start of Period 7, the Center was still searching for someone to fill this position. In mid-June 2016, **Kedrick Perry** was hired and onboarded within the Center; however in the months without a Diversity Director, the Center's staff needed to limit their expansion into creating and developing the Education legacy.

2. Educational Activities

During Period 7, the Center graduated 4 graduate students and 11 postdocs. In addition, 11 undergraduates who were research interns with the Center, either through one of the REU programs (E^3S REU or ETERN) also received their baccalaureate. To date, E^3S has graduated 140 graduates (52 undergraduates, 51 graduates, and 37 postdocs). These students and postdocs have gone on to pursue careers in industry, academia, and national research laboratories around the globe (see Graduates Table, Centerwide Output). These Center alumni have benefited from the Center's formal and informal training programs and opportunities.

Since the start of the Center, E^3S Director, **Eli Yablonovitch** has been teaching biennially a graduate level course on low energy electronics with a strong focus on E^3S topics and perspectives. In Period 7, the course, a listed UC Berkeley course, was taken by 7 graduates students from two of the five E^3S member institutions, and 2 postdocs from two member institutions.

The Center also offers a variety of informal training opportunities for graduate students and postdocs including: presenting, both oral and poster, at seminars and during Center events; mentoring of undergraduates; group analysis of competing research; participating in the REU intern selection process; serving a poster judges, and conducting scientific demonstrations at outreach events. In Period 7, 25 graduate students and 10 postdocs took advantage of these practical training opportunities.

These informal training opportunities are part of the professional development opportunities of the Center. Given the number of opportunities available, the Center has also developed the E^3S Professional Development Program (E^3S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences. Upon completing enough areas, a student/postdoc will receive a Leadership Certificate. Thus far, seventeen students have earned a certificate of completion, of these, 1 was awarded in Period 7.

More than half, 53 (60%) of the E^3S students participated in a training area in Period 7, with 35 (40%) having completed at least one area.

The Center also offers training in areas that it deems important in developing a scientist /engineer. Incoming students and postdoc are required to complete an online ethics training. All mentors of REU students receive training in project management and interactions between mentor and mentee. In Period 7, 16 students and postdocs received training in these area. In addition, in Period 7, the Center offered a workshop on professional etiquette that was attended by 18 students and postdocs.

The recent 2016 survey of graduate students and postdocs identified the impact of the Center's education programs on increasing the respondents' understanding of low energy consumption device science and technology (**Figure 3.1).** Students also indicated that the Center has positively impacted their professional development and interests in energy efficient electronics (**Figure 3.2**).

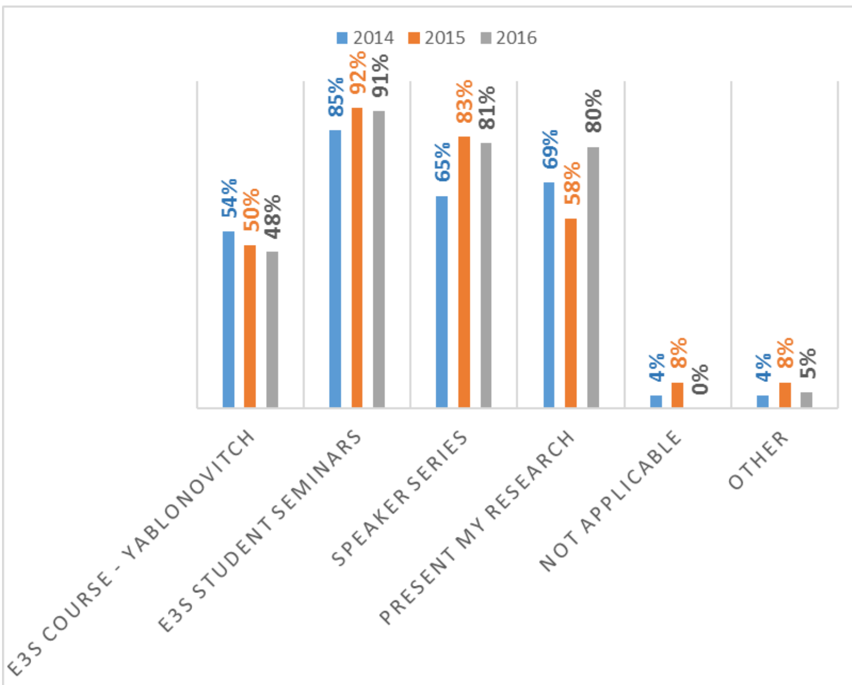


Figure 3.1. Graduate students and postdocs indicated the Center's educational activities are sharpening their understanding of low energy consumption device science and technology

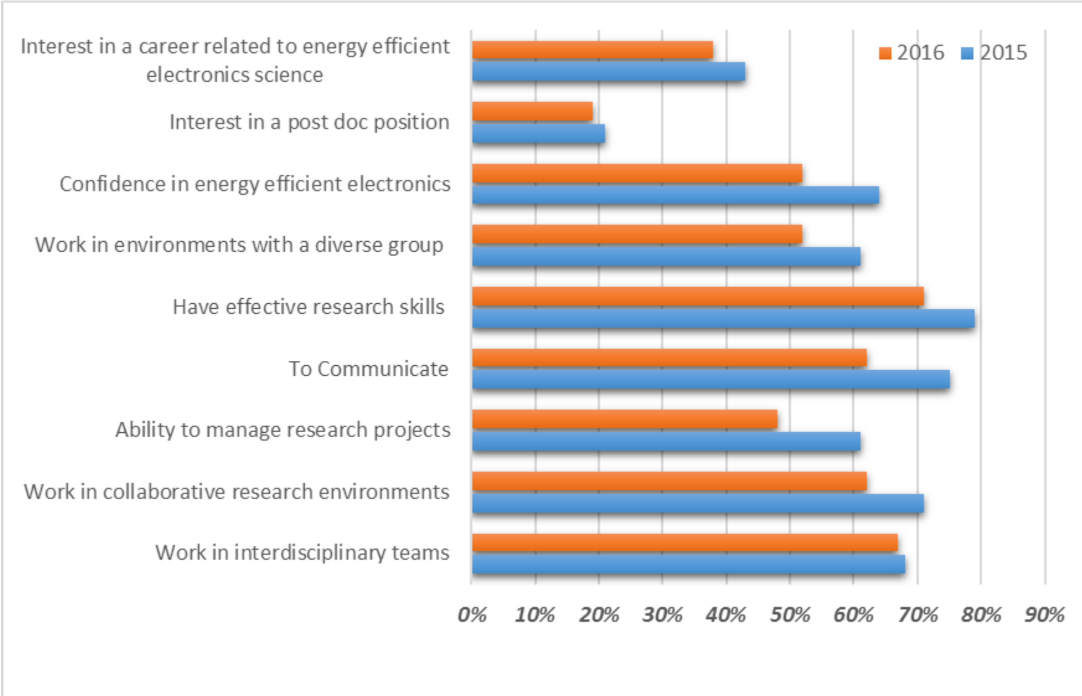


Figure 3.2. Graduate Students and postdocs indicated that the Center has positively impacted their professional development and interests

The Center is also impacting undergraduate education by offering research opportunities. Students of the member institutions participate in the ETERN program that offers paid 10 week internships during the academic term. In Period 7, there were 3 ETERNs at FIU and UTEP.

The Center also manages three REU programs for undergraduates from 4 year institutions and community colleges. Five community college students and 15 undergraduates from 4 year institutions were hosted in E^3S or E^3S affiliated research groups at MIT and Berkeley. In alignment with the Center's focus community college education, four E^3S faculty supported the professional development of five community college teachers in Period 7 with the goal of enhancing STEM classroom instructions. One community college professor developed teaching materials introductory physics course. The remaining four community college instructors are continuing to develop their curriculum based on the 8 weeks of research they did over the summer.

The following sections provide details in support of the above summary of the state of Education in Period 7.

2a. Internal Educational Activities

The internal educational activities that were initiated in previous reporting periods continued in Period 7. 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 3 interns conducting research during the academic terms at 2 institutions.

Table 3.2.

Activity Name	E^3S Course – EE 290B: Advanced Topics in Solid State Devices
Led by	**Eli Yablonovitch** (Berkeley)

Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 9 Graduate Students: 4 Berkeley, 3 MIT Postdocs: 1 Berkeley, 1 Stanford

One of the Center's goals for its members is to receive formal training in technical topics that are applicable to the Center. **Eli Yablonovitch,** Center Director, developed a UC Berkeley, EE 290: Advanced Topics in Solid State Devices, to be the key training venue. This course was first taught in Fall 2010, at the inception of the Center. In Period 7, **Eli Yablonovitch** taught EE 290 again. 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 nano-scale impedance matching transformers, including plasmonics, new forms of amplification using giant magneto-resistance and other spintronic effects, nano-mechanical switching elements that are capable of very low voltage operation, low-temperature electronics, and electro-chemical switching elements. This course was taught at UC Berkeley and offered to members at all institutions through videoconferencing technology and online posting of course material. The enrollment count for this course was 20, including 9 E^3S members from Berkeley, MIT, FIU, and UTEP; and 11 non-E^3S members.

Table 3.3.

Activity Name	E^3S Research Seminars
Led by	**Michael Bartl** (Berkeley) and Graduate Student Postdoc Council (GSPC)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 401 Undergraduate Students: 64 Berkeley, 16 MIT, 1 UTEP Graduate Students: 120 Berkeley, 28 MIT, 1 Stanford, 6 UTEP, 4 FIU Postdocs: 52 Berkeley, 2 MIT, 1 Stanford, 4 UTEP

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. The speakers are mainly graduate students and postdocs, who present the progress of their research. Occasionally, E^3S faculty present new projects, and industry partners have presented the research efforts in their company. Period 7 is expected to conclude with 13 seminars; a list of scheduled seminars can be found at this website: http://www.e3s-center.org/research/rsh-seminars.htm. For attendance at the seminars, please see Appendix D.

Table 3.4.

Activity Name	Sixth 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 – 72 Undergraduate Students: 1 UTEP Graduate Students: 16 Berkeley, 6 MIT, 3 FIU, 2 UTEP Postdocs: 4 Berkeley, 2 MIT, 1 Stanford, 1 UTEP

The Annual Retreat has continued to be a multi-purpose venue. One purpose is to educate graduate students and postdocs through two days of presentations and discussions. Part of the education is the opportunity to present one's research at a poster session attended by representatives of member companies. There were 19 posters at the 2016 Annual Retreat presented by 13 graduate students (8 Berkeley, 1 FIU, 3 MIT, 1 UTEP), 5 postdocs (1 Berkeley, 2 MIT, 1 Stanford, 1 UTEP), and 1 undergraduate (UTEP). For a list of posters, please see Appendix I.

Table 3.5.

Activity Name	Poster Presentation at the External Advisory Board Meeting
Led by	**Michael Bartl** (Berkeley)
Intended Audience	External Advisory Board
Approx. Number of Attendees (if appl.)	Total – 8 Undergraduate Students: 1 Berkeley Graduate Students: 5 Berkeley Postdocs: 2 Berkeley

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

Table 3.6.

Activity Name	Fifth Annual Student and Postdoc Retreat
Led by	**Lea Marlor** (Berkeley), **Kedrick Perry** (Berkeley), and GSPC
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 10 Undergraduate Students: 1 UTEP Graduate Students: 6 Berkeley, 1 UTEP Postdocs: 1 MIT, 1 UTEP

In August, the Center hosted its 6th Annual Student and Postdoc Retreat for graduate students and postdocs. Graduate students and postdocs spent the day in breakout sessions organized by research themes. Topics also discussed were the E3S Rotation Program, the Graduate Student and Postdoc Council, ways to increase attendance at future student retreats, and the NSF Professional Development workshop.

Table 3.7.

Activity Name	E^{3}S Internship (ETERN)
Led by	**Lea Marlor** (Berkeley) and **Kedrick Perry** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx. Number of Attendees (if appl.)	Total – 3 Undergraduate Students: 1 FIU, 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 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 7, we had 3 participants. These students were advised by E^{3}S faculty and mentored by E^{3}S graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs such as research seminars.

Table 3.8.

Activity Name	E^{3}S Lab Tours
Led by	**Lea Marlor** (Berkeley), **Akshay Pattabi** (Berkeley), **Bivas Saha** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx. Number of Attendees (if appl.)	Total – 18 Undergraduate Students: 1 MIT, 1 UTEP Graduate Students: 5 Berkeley, 2 MIT, 4 FIU, 1 UTEP Postdocs: 1 Berkeley, 1 MIT, 1 UTEP, 1 Stanford

The Center's graduate students and postdocs requested that student led lab tours be hosted at the annual retreats and site visits. The goals of these tours are to increase awareness of what the other students are doing, foster relationships between the member institutions, and to offer the opportunity to see different equipment being used. This year was the first year that such lab tours were held, and the students visited two labs, Prof. **Jeffrey Bokor**'s and Prof. **Junqiao Wu**'s were shown by a graduate student and postdoc from each of their respective labs.

Table 3.9.

Activity Name	E^3S Rotation Program
Led by	**Michael Bartl** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 18 Graduate Students: 1 FIU, 1 UTEP

The Center allows for its graduate students and postdocs to go to a partner institute, different from their home university to conduct research for a period of time. This year, two students spent the summer doing research at UC Berkeley. **Aldo Vidana** (UTEP) worked in Prof. **Ali Javey**'s lab under the guidance of graduate student, P. Zhao. His project worked on the 2D stritch. **Ali Hadjikhani** (FIU) worked in Prof. **Jeffrey Bokor**'s lab with postdoc **Jeongmin Hong** on a project using the helium focused ion beam.

2b. *Professional Development Activities*

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

Table 3.10.

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 – 35 Graduate Students: 16 Berkeley, 5 MIT, 2 FIU, 1 UTEP, 1 Stanford Postdocs: 5 Berkeley, 2 MIT, 2 Stanford, 1 UTEP

Students and postdocs are provided with a number of programmatic activities within the Center aimed at professional development. These programs offer different areas of development: leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship. E^3S PDP is a framework to ensure a student or postdoc receives well-rounded professional experiences (Appendix E). For a certificate of completion, students and postdocs must complete: 1) at least one activity in the area of leadership, outreach, or mentoring; and 2) at least one education activity in three other training areas (teaching, proposal writing, science communication, and entrepreneurship). Thus far, seventeen students have earned a certificate of completion, of these, 1 was awarded in Period 7. Over half, 53 (60%) of the E^3S students started a training area by the end of Period 7, and 35 (40%) have completed at least one training area by the end of Period 7.

Table 3.11.

Activity Name	Project Management and Mentor Training
Led by	**Lea Marlor** (Berkeley)
Intended Audience	Graduate Student and Postdoc Mentors
Approx. Number of Attendees (if appl.)	Total – 16 Graduate Students: 12 Berkeley Postdocs: 4 Berkeley

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

Table 3.12.

Activity Name	Professional Etiquette Training
Led by	**Lea Marlor** (Berkeley)
Intended Audience	All Graduate Student and Postdocs
Approx. Number of Attendees (if appl.)	Total – 18 Undergraduate Students: 1 MIT, 1 UTEP Graduate Students: 5 Berkeley, 2 MIT, 4 FIU, 1 UTEP Postdocs: 1 Berkeley, 1 MIT, 1 UTEP, 1 Stanford

Additional opportunities for leadership experiences for graduate students and postdocs were provided at this year's annual retreat in form of a professional etiquette workshop. The training, conducted by Berkeley's J. Anderson, discussed networking, business communication, and business dining etiquette.

Table 3.13.

Activity Name	REU Selection Committee
Led by	**Lea Marlor** (Berkeley)
Intended Audience	Postdocs as primary target
Approx. Number of Attendees (if appl.)	Total – 16 Graduate Students: 8 Berkeley, 4 MIT, 1 FIU Postdocs: 1 Stanford, 1 UTEP, 1 MIT

Special emphasis is given to recruit postdocs to serve on the selection committee for the E^3S Research Experience for Undergraduates (REU) program. Due to the substantial number of applications received, graduate students were also invited to participate in 2016. Each member of the selection committee reviews the application material, including personal statement, transcript, and letters of recommendations of ~5 applicants. Based on their review process, the postdocs and graduate students provided a list of applicants that should be considered for placement in a REU summer research project.

Table 3.14.

Activity Name	REU Poster Review
Led by	**Lea Marlor** (Berkeley)
Intended Audience	Undergraduate Students at Center's Institutions
Approx. Number of Attendees (if appl.)	Total – 12 Graduate Students: 10 Berkeley, 1 UTEP, 1 FIU

The Center hosted three REU programs, one for upper division undergraduates, one for students attending an HBCU institution, and another for community college students in conjunction with a REU site award. In addition to the REU programs, the Center also hosted an RET program for community college faculty, also in conjunction with a site award. These programs concluded with a joint poster session of all REU and RET participants. This offered a professional development opportunity for graduate students and postdocs to be reviewers. In Period 7, 12 graduate students and postdocs evaluated the posters based on the following criteria: presentation skills, poster layout, and content (problem, methods, results & understanding). Each member of the review panel evaluated 4-5 posters so that all of the summer students had two evaluations of their work. At the conclusion of the poster session, assessments were anonymously shared with the REU intern to provide them feedback on their performance.

2c. *External Educational Activities*

Table 3.15.

Activity Name	E^3S Teacher Fellows Program
Led by	**Michael Bartl** (Berkeley)
Intended Audience	Community College Professors
Approx. Number of Attendees (if appl.)	Total: 5 URM: 2

With the Center's focus on creating a pipeline of community college students who pursue a baccalaureate degree in science and engineering, it is imperative for the Center to engage community college faculty. These individuals can further integrate E^3S science and research findings into the community college curriculum and increase community college students' awareness and knowledge of low-energy electronic devices. In Period 7, the Center hosted five community college faculty members in our E^3S Visiting Faculty Program which allows a community college faculty to spend six to nine weeks in a research laboratory associated with the Center or develop curricula mentored by Center members. Leveraging a community faculty program that NSF awarded to the Center's PI, **Eli Yablonovitch**, E^3S Visiting Faculty participated in a pedagogy workshop that taught community college faculty participants about context-based and online teaching. The five E^3S visiting community college faculty are described below.

Virgil Shields, a faculty member in the Department of Engineering at Los Angeles Trade Technical College (LATTC), one of the Center's education partners, was hosted by the Center as he developed videos and online content for his introductory physics courses that is currently being implemented.

Leonard Filane, a physics and math instructor at College of Marin, conducted eight weeks of research in the laboratory of Prof. **Ali Javey** in Berkeley, mentored by postdoc, **Wei Gao**. The RET program calls for the introduction of new curricular materials that incorporate some of the new concepts in the summer research. In Fall 2016, the visiting physics instructor implemented this research into his Electricity and Magnetism Physics course.

Samir Abboud, an engineering instructor at Laney College conducted his 8-week project in Prof. **Junqiao Wu**'s lab, and was mentored by postdoc, **Hwan Sung Choe**. **Binod Dhakal**, a physics instructor at Diablo Valley College, worked in Prof. **Eli Yablonovitch**'s lab, and was mentored by graduate student **Tianyao Xiao**. **Kofi Opong-Mensah**, a chemistry professor at the College of Marin, conducted research in Prof. **Felix Fischer**'s lab, and was mentored by postdoc **Hyangsoo Jeong**. These three remaining professors are in the process of implementing their projects into coursework.

Table 3.16.

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

The E^3S E-book is a legacy development in Period 7. The book will discuss E^3S research and be written at a high school level. Each research theme has a dedicated section within the book, with the theme leaders deciding the subjects and chapters within each section. At the end of Period 6, each theme leader will have produced an outline for their section. Graduate students and postdocs will be creating the content for the book in Period 8.

Table 3.17.

Activity Name	Bay Area Science Festival
Led by	**Lea Marlor** (Berkeley)
Intended Audience	The San Francisco Bay Area Community
Approx. Number of Attendees (if appl.)	Total- 8 Undergraduate Students: 2 Berkeley Graduate Students: 6 Berkeley

Each fall, a science festival is held at AT&T Park in San Francisco that showcases fun and exciting science to the general population. This year was the fourth year that E^3S participated in the event. **Lea Marlor** led 8 students in demonstrating how 2D materials (graphene) conduct electricity. More senior participants were also introduced into the Center's goal of using 2D materials to tackle the energy efficiency problems faced in our current electronics. More than 30,000 people attended the fair, and of those, approximately 500 people participated in the E^3S demonstration.

2d. Integration of Education and Research

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

2e. Performance Against Metrics

During this reporting period, the Center has compared the educational programs with the Period 5 targets. The table below displays these data and future metrics to measure education success.

Table 3.18.

Objective	Metric	Targets	Results					
			P 2	P 3	P 4	P 5	P 6	P 7
Education	Center graduates completed E^{3}S training	Period 2: Baseline	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)	4 (27%)
		Period 3: 50%						
		Period 4: 50%						
		Period 5: 50%						
		Period 6: 15%						
		Period 7: 30%						
	Students accessing online courses of the Center	Period 6: 50	(new for P6-10)				0	0
		Period 7: 75						
	Undergraduates who pursue advanced degree in science and engineering	Period 3: 5%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)	36 (69%)
		Period 4: 30%						
		Period 5: 35%						
		Period 6: 40%						
		Period 7: 45%						
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Period 2: Baseline	n/a	3 (100%)	6 (100%)	7 (100%)	6 (100%)	4 (80%)
		Period 3: 5%						
		Period 4: 80%						
		Period 5: 80%						
		Period 6: 85%						
		Period 7: 85%						
	Pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline	n/a	25 (32%)	62 (42%)	101 (51%)	133 (56%)	163 (56%)
		Period 4: 70%						
		Period 5: 70%						
		Period 6: 80%						
		Period 7: 80%						
	Students and postdocs serving in leadership roles in the Center	Period 2: Baseline	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)	19 (26%)
		Period 3: 15%						
		Period 4: 20%						

		Period 5: 25%						
		Period 6: 30%						
		Period 7: 30%						

2f. Education Activities in Period 8

Much of Period 8 will be spent in continuing the established education programs and continuing in the creation and development of the Center's Education legacy. The outlines of each theme's section in the E-book will be completed by the end of Period 7, and the Center plans to have a first draft of the book completed during Period 8.

IV. KNOWLEDGE TRANSFER

1a. *Goals and Objectives*

In alignment with the mission and vision of the Center for E^3S as a Science and Technology Center fostering groundbreaking new science discoveries and fertilizing new technologies, knowledge transfer is central to E^3S and a key metric of its success. The Center regards knowledge transfer as a two-way street by establishing partnerships that will accelerate the Center's research and programmatic endeavors, while creating new knowledge that can be shared with industry, academia and research labs. The Center's goal is to both develop novel, highly efficient electronic technologies and engaging stakeholders of various science and engineering disciplines and at different educational levels to participate in these new opportunities.

At the Center for E^3S, knowledge transfer happens at two levels: 1) Knowledge transfer within the Center's main partners as a cross-fertilization of ideas and projects, and 2) knowledge transfer throughout the technology and education ecosystem in which the Center participates. On the research side, the reach of knowledge transfer includes 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 knowledge transfer channels of the Center for E^3S have remained unchanged from last year's report, and include:

- 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. *Performance Metrics*

Objective	Metrics	Frequency	Targets
Knowledge Transfer	Center publications	Yearly	Periods 2 – 5: Yearly: 18 Period 6: 25 Period 7: 25
	External citations of publications *(cumulative)*	Yearly	Period 3: 10 Period 5: 100 Period 6: 25% yearly increase Period 7: 25% yearly increase
	Talks at peer-reviewed conferences *(added in Period 6)*	Yearly	Period 6: 12 Period 7: 12
	Center sponsored symposia & workshops	Bi-annually	Period 2: baseline Period 3: 0 Period 4: 1 Period 5: 0 Period 6: 2 Period 7: 1

	Website hits & unique visitors *(discontinued)*	Yearly	Period 2: Baseline Period 3: 20% increase
	Contacts with industry • Talks & Meetings • Presentations by industry	Yearly	 Period 2: 18 Period 3+: 36 yearly Yearly: 2
	Research Collaboration with industry	Yearly	Period 4: 1 Period 5: 2 Period 6: 3 Period 7: 3
	Patents Disclosures/Provisional	Yearly	Period 3: 3 Period 4: 3 Period 5: 5 Period 6: 2 Period 7: 2
	• Patent Application Filed/Granted	Yearly	Period 4: 0 Period 5: 3 Period 6: 1 Period 7: 2
	• Center's alumni into relevant industries	Yearly	Period 5: 50% Period 6: 30% Period 7: 30%
	Center's alumni pursuing research in disciplines related to the Center at academia & research labs *(added in Period 6)*	Yearly	Period 6: 30% Period 7: 30%
	Technology development attributable to Center's research • Low energy devices • Enabling other applications	Yearly	Period 6: 0 Period 7: 0
	• Number of external articles on the Center *(discontinued)*	Yearly beginning in Period 3	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase

1c. Problems Encountered

As indicated in the last annual report, the Center website had been modernized this year and received a facelift. During the facelift, the Center decided to also add a Center for E^3S Blog to the new website. Launch of this new E^3S Blog has been delayed due to a delay in the hiring process of a new website developer. The new Blog is expected to go online early in 2017.

2a. Knowledge Transfer Activities

Dissemination of results and outcomes from research, education and diversity activities remain the key knowledge transfer avenue of the Center for E^3S. As in previous years, these efforts have been broadly supported by all of the Center's researchers and key staff personnel through publications in scientific peer-reviewed journals, presentations at peer-reviewed conferences, scientific meetings, universities and industry, and knowledge exchange with a wide range of communities *via* public and private meetings.

Since the last annual report, researchers at the Center for E^3S have published 29 papers in journals, and 10 are under review. Moreover, the papers from 12 talks, presented at peer-reviewed conferences, have been published as conference proceedings. In addition, Center members presented 38 papers at other peer-reviewed conferences, including presentations by REU program alumni.

As stated above, the Center for E^3S considers knowledge transfer a two-way road and actively solicits information and results from various sources external to the Center. For example, the Center seeks input from its Industrial Research Board composed of companies that the Center considers to be key players and the areas of research most closely related to the Center. This occurs in the form of seminars by invited external speakers, Center students and postdocs visiting companies to learn about other low-energy electronics programs, and organization of education and diversity workshops to bring educators from other institutions into the Center.

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

An important knowledge transfer activity have been the biennial Berkeley Symposia for Energy Efficient Electronic Systems organized by the Center in odd-numbered years. We are currently in the planning stages for the 2017 Berkeley Symposium, which will be held in October, and for the first time, will be a joint meeting with the Steep Transistor Workshop. In addition, we have plans to partner up with the IEEE S3S Conference and become a satellite event.

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

- *Dissemination of Results*

  The main knowledge transfer venue has continued to be dissemination of research and education results by E^3S researchers through publications in peer-reviewed journals and at scientific conferences. The Center has also continued to provide avenues for its REU interns to go to scientific conferences and present their research activities through talks and posters.

Table 4.2. Dissemination of the Center's Research Results in Peer-Reviewed Journals		
Led by	**E^3S 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, staff, and collaborators have published 29 papers, all in peer-reviewed journals. An important performance metric included in the Strategic Plan is the number of citations of the Center's publications. By the submission of this report the cumulative citations for the 155 papers attributed to the Center was 2718, an increase of 58 percent from last year.

Table 4.3. Dissemination of the Center's Research *via* Proceedings of Peer-Reviewed Conferences		
Led by	**E^3S Faculty**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford	Palo, CA
4.	UTEP	El Paso, TX

19 talks by researchers from Berkeley, MIT and Stanford were published in conference proceedings in Period 7. Twelve of these talks were in proceedings of major conferences, like IEEE International Electron Devices Meeting, Device Research Conference and IEEE Int'l MEMS conference.

Table 4.4. Presentations by Center REU Alumni at Peer-Reviewed Conferences		
Led by	**Lea Marlor**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	CUR Research Experiences for Undergraduates Symposium	Arlington, VA
3.	SACNAS Annual Conference	Long Beach, CA
4.	Annual National Conference on Undergraduate Research (NCUR)	Memphis, TN

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 7, two community college students presented their work at the SACNAS Conference in October and one community college student presented his work at the CUR Research Experiences for Undergraduates Symposium in October. In addition, one community college student applied to present at the Annual National Conference on Undergraduate Research, which will be held in Memphis, TN, in April 2017.

Table 4.5. HBCU E^3S Workshop		
Led by	**Josephine Yuen, Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Hampton University	Hampton, VA
3.	Morgan State University	Baltimore, MD
4.	Norfolk State University	Norfolk, VA
5.	Jackson State University	Jackson, MS

The Center for E^3S took the lead in co-organizing a workshop in March 2016 for the Berkeley HBCU summer REU program (Tsu-Jae King Liu, PI). This REU program is funded by the University of California Office of the President and is managed and operated by E^3S staff as part of our summer REU portfolio. The workshop attendees included representatives of all four HBCU schools that participated in the 2016 HBCU REU program. The workshop agenda (see

Appendix H) featured presentations by HBCU and UC Berkeley faculty as well as information sessions about the REU program and the UC Berkeley EECS graduate program. An expanded version of this workshop in spring 2017 is in the planning stages.

Table 4.6. Granted Patents & Patent Applications		
Led by	**E[3]S Researchers**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA

So far, in Period 7, E[3]S researchers at UC Berkeley and MIT applied for three patents (two from Theme I and one from Theme III). In addition, two patents were granted in 2016 to MIT researchers. Both of the patents were about Theme II research results: One of the patents was on thin-film membrane transfer, and the other patent was related to nanomechanical switching using molecular layers (the "Squitch").

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

  As a Science and Technology Center, the Center for E3S actively seek possibilities of transferring some of the knowledge acquired in its research projects to other organizations, including industry, research labs, and academia. With the recent substantive progress in several of the Center's research projects, several efforts with the goal to transfer knowledge and develop applications outside the main scope of the Center have continued.

Table 4.7. Squitch Switches as Analog Valves		
Led by	**Jeffrey Lang, Vladimir Bulovic and Timothy Swager**	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	MIT Lincoln Labs	Cambridge, MA

MIT Lincoln Labs has continued to explore the Squitch approach as analog valves by funding process development on their unique nanofabrication capabilities and perform testing studies.

Table 4.8. RIE process with Digital Etch Technology for III-V Features of High Aspect Ratios		
Led by	**Jesus del Alamo**	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	Lam Research	Fremont, CA
3.	Applied Materials	Santa Clara, CA
4.	Northrop Grumman	Sacramento, CA

Developed for III-V nanowires, as part of Theme I's TFET research, the REI digital dry etch technology has found great use in other research programs in the del Alamo group. They have proven to be transformational. Excellent devices results have demonstrated the potential of III-V MOSFETs for future CMOS. During Period 7, Jesus del Alamo has been working with one company (Lam Research) and an international research institute (IMEC in Belgium) to assess the technology for broader semiconductor applications.

Table 4.9. Materials Processing and MEMS Device Fabrication		
Led by	**David Zubia, Ali Javey, Tsu-Jae King Liu**	
Organizations Involved		
	Name	*Address*
1.	UTEP	El Paso, TX
2.	UC Berkeley	Berkeley, CA

This is an example of knowledge transfer between different research themes within the Center. Initiated in Period 6, David Zubia (UTEP; Theme II) has been collaborating with Ali Javey (UC Berkeley; Theme I) to transfer the Javey group knowledge of 2D materials from nanoelectronics applications to nanomechanics applications at UTEP's Electrical Engineering Department. This transfer has been intensified in this period through exchange of a graduate student (as part of the Center's 9-week summer rotation program) and a postdoc (moved from UTEP to Tsu-Jae King Liu's lab at UC Berkeley).

- *Knowledge Transfer into the Center*

  Since its inception, the Center for E^{3}S has embraced a two-way knowledge transfer strategy through the formation of strong ties to industry and research labs, and transferring knowledge from these partners back into the Center. These strong interactions and exchange of ideas with outside partners have stimulated new ideas and enabled Center researchers (faculty, postdocs and students) to learn from other leaders in related research and technology areas.

Table 4.10. Annual Meeting and 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

The five companies comprising the E^{3}S Industrial Research Board were invited again this year to the Center's Annual Retreat to advise the Center on its research direction and ensure that the approaches are practical. Four of the five members send representatives (see table above) to attend all the research presentations and discussions of the annual retreat (see agenda, Appendix I). In addition, the Industrial Research Board members met separately with the E^{3}S leadership to provide detailed feedback on the Center's research accomplishments and directions.

Table 4.11. Seminars by Invited Speaker		
Led by	**Michael Bartl**	
Organizations Involved		
	Name	*Address*
1.	Lawrence Berkeley National Lab (LBNL)	Berkeley, CA
2	Francis Bitter National Magnet Laboratory	Cambridge, MA
3.	Korea Advanced Institute of Science and Technology (KAIST)	Daejeon, South Korea
4.	UC Berkeley	Berkeley, CA
5.	MIT	Cambridge, MA
6.	Stanford	Palo Alto, CA
7.	UTEP	El Paso, TX
8.	FIU	Miami, FL

In this period, the Center management organized two seminars by external speakers: Dr. P. James Schuck (LBNL) and Prof. Kyoungsik Yu (KAIST). In addition, the Center for E^{3}S Student and Postdoc Council was encouraged to select a third invited speaker. The council invited Dr. Jajadeesh Moodera (Francis Bitter National Magnet Laboratory) who gave a talk on "Surfaces, Interfaces, Spins … Controls all - from exchange interaction to quantum transport to molecular spintronics". More details about seminars can be found at *http://www.e3s-center.org/research/rsh-seminars.htm*. It should be emphasized that these seminars also attracted attendees from outside the Center, participating either in person or *via* Webex.

Table 4.12. Tour of Marvell Nanofabrication Lab at Annual Student Retreat		
Led by	**E^{3}S Student and Postdoc Council**	
Organizations Involved		
	Name	*Address*
1.	Marvell Nanofabrication Laboratory	Berkeley, CA
2.	UC Berkeley	Berkeley, CA
3.	MIT	Cambridge, MA
4.	Stanford	Palo Alto, CA
5.	UTEP	El Paso, TX
6.	FIU	Miami, FL

As part of the 2016 Annual Student Retreat at UC Berkeley the Center for E^{3}S Student and Postdoc Council organized a tour of research labs and fabrication facilities at the Berkeley campus. This activity was initiated as a means to exchange information between students and postdocs from different E^{3}S campuses and to learn about the facilities available in the Marvell Nanofabrication Laboratory at UC Berkeley. The tour of the Marvell Nanofabrication Laboratory was led by Nanolab executive director Dr. Bill Flounders.

Table 4.13. Student Visit of Lam Research Facilities	
Led by	**Lea Marlor**
Organizations Involved	

	Name	Address
1.	UC Berkeley	Berkeley, CA
2.	Lam Research	Fremont, CA

E^{3}S graduate students and the summer REU student cohort visited the headquarters of our industry partner Lam Research. This visit was coordinated by our education manager (Lea Marlor) and Nerissa Draeger from Lam Research. The visit included a tour of the manufacturing units, including the impressive cleanroom facilities. Students also had the chance to speak to representatives of Lam Research.

- *Education Knowledge Transfer*

  The Center's education and diversity programs are very active in interacting with the broader community and engaging in knowledge transfer through written and oral dissemination of best practices, curriculum development and dissemination, and in-person outreach.

Table 4.14. Presentation at ASEE		
Led by	**Lea Marlor**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	ASEE Conference, June 2016	New Orleans, LA

E^{3}S education and outreach manager, Lea Marlor, presented a paper at the peer-reviewed conference, ASEE in June 2016 on "The Impact of Summer Research Experiences on Community College Students Self Efficacy". This paper was co-authored with Catherine Amelink, external evaluator of the Center for E^{3}S.

2b. Outcomes

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

2c. Performance Against Metrics

Metric	Targets	Results					
		P 2	P 3	P 4	P 5	P 6	P 7
Center publications	Period 2: 18 Period 3: 18 Period 4: 18 Period 5: 18 Period 6: 25 Period 7: 25	17	17	19	39	45	41
	Period 6: 12	(new for P6-10)				14	12

Talks at peer-reviewed conferences	Period 7: 12						
Center sponsored symposia & workshops	Period 2: Baseline Period 3: 0 Period 4: 1 Period 5: 0 Period 6: 2 Period 7: 1	1	0	1	0	1	1
External citations of publications *(cum)*	Period 3: 10 Period 4: 100 Period 5: 100 Period 6 - 10: 25% increase	15	178	393	719	1724	2718
Contacts with industry:							
• Talks & Meetings	All Periods: 36	66	20	42	62	35	42
• Industry Presentations	All Periods: Yearly: 2	4	2	6	3	5	2
Research collaboration with industry	Period 4: 1 Period 5: 2 Period 6: 3 Period 7: 3	0	1	1	4	6	8
Patent disclosures							
• Disclosure/Provisional	Period 3: 3 Period 4: 3 Period 5: 5 Period 6: 2 Period 7: 2	1	0	1	0	2	1
• Patent Application Filed	Period 4: 0 Period 5: 3 Period 6: 1 Period 7: 2	1	0	0	0	4; 1 granted	4; 2 granted
Technologies attributable to Center's research		(new for P6-10)				0	0
• Low energy devices	Period 6: 0 Period 7: 0						
• Enabling other applications	Period 6: 0 Period 7: 0						
Center's alumni into relevant industries	Period 5: 50%	Students: 0%	Students: 64% (7)	Students: 16% (2)	Students: 16% (6)	Students: 50% (12)	Students: 22% (2)

	Period 6: 30% Period 7: 30%	Postdocs: 100% (1)	Postdocs: 33% (2)	Postdocs: 20% (2)	Postdocs: 40% (4)	Postdocs: 13% (1)	Postdocs: 18% (2)
Center's alumni pursuing research in academia & research labs in disciplines related to the Center	Period 6 -10: 30%	(new for P6-10)				Students: 38% (9) Postdocs: 88% (7)	Students: 78% (7) Postdocs: 82% (9)

2d. Transfer Activities in Period 8

A new knowledge transfer avenue that will be released at the end of Period 7 and come to full fruition in Period 8 is the Center for E^3S Blog Site. This blog site will be integrated into the E^3S main website and will feature a stream of blog entries from Center members including the executive director, the diversity director, the education manager, and a representative of the E^3S Student and Postdoc Council. In addition, the blog is open to any other Center members. Blog entries will be another avenue to keep Center members, affiliates, as well as the general public informed about Center activities and programs, key outcomes, and general stories related to energy efficient electronics.

Another new transfer of knowledge activity will be the launch of a Center for E^3S site on the *nanoHUB.com* website platform. This platform will initially be used mainly for educational purposes and will include publication of an open-access e-book on energy efficient electronics. The e-book project is currently at an early stage of planning of the main chapters that will be included.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

Collaborations within and with external partners are at the heart of the Center for E^3S. As an NSF Science and Technology Center, the multi-institutional structure of E^3S is ideally suited to extend its collaborative nature to external partners. In fact, the Center considers external partners as critical components to its success at all Center aspects: research, education, knowledge transfer and broadening participation. The Center's researchers have thus established both formal and informal partnerships with researchers in academia, industry, and research labs as they pursue their scientific investigations. As discussed in detail in the Knowledge Transfer section of this report, partnerships with industry are one of the cornerstones of the two-way knowledge transfer strategy of E^3S. The education and diversity programs leverage the experience, expertise and resources of campus partners at the lead and subaward institutions to deliver highly successful programs. In Period 7, the Center has continued to execute and enhance its partnership strategy to enable successful achievement of all its goals.

1b. Performance Metrics

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

The metrics for external partnerships, in part, co-align with the "knowledge transfer with industry" metrics. The rational for this lies in the fact that the Center for E^3S regards industry partnerships as critical to the success of practical implementation of its research outcomes. However, this—in no way—implies that E^3S does not consider external partnerships at all aspects of the Center's work critical to its success. Indeed, the Center has continued to engage external partners to accelerate its work towards the Center's goals.

As in past reporting periods, the Center will continue to track the number of contacts with industry in two categories: i) talks given to and meetings with industry; ii) presentations by industry. The two metrics, in place since the start of the Center, measure the sharing of information. New in this period is the metric, number of research collaborations, to measure the depth of engagement with industry.

1c. Problems Encountered

As reported last year, the E^3S Squitch team planned to enter into a formal 1-year joint development partnership with MIT Lincoln Labs (MITLL). However, due to MITLL personnel shifts, the project was suspended and did not resume until late 2015. In Period 7, MITLL has continued to explore the Squitch approach as analog valves by funding process development on their unique nanofabrication capabilities and perform testing studies as part of an informal partnership with the Squitch team.

2a. Activities in Period 7

As in previous periods, the Center has engaged industry partners in order to accelerate research and facilitate knowledge transfer.

- Participation as a member in the E^{3}S Industrial Research Board has continued to be the primary route for companies to engage with the Center on a sustained basis; see Center Management section. The five member companies are: Applied Materials, Hewlett-Packard Enterprise, IBM, Intel and Lam Research. Besides serving as advisors to provide the Center with industry perspectives, these companies support the Center's activities, including financial support in limited cases. In Period 7, four of the five member companies had additional engagement with the Center beyond an advisory level.
    - Applied Materials has a partnership with **Jesus del Alamo** (*MIT*) for evaluating the potential of the high aspect ratio digital edge technology developed for nanowire semiconductors.
    - Lam Research has also continued to conduct laboratory evaluation of the high aspect ratio digital etch technology of the **Jesus del Alamo** group for broader semiconductor applications.
    - Intel Corporation has elected Nanomechanics Theme Leader **Tsu-Jae King Liu** to serve on its Board of Directors.
    - IBM Yorktown researches have collaborated with the **Yablonovitch** and **Antoniadis** groups in investigating Auger effects in TFETs. This has led to a joint publication.
- Other companies work with the Center in focused and limited manner.
    - Western Digital has continued to provide funding for early access to the sub-10μm STT-MTJ spintronics research in the **Khizroev** group (*FIU*).
    - Northrop Grumman is another company evaluating the digital etch technology broader semiconductor applications.

E^{3}S faculty have primarily been engaged in ad hoc research collaborations with other researchers, the most substantive being the partnership between MIT Lincoln (MITLL) and the E^{3}S Squitch team of **Bulović, Lang** & **Swager** (*MIT*) that includes funding process development on their unique nanofabrication capabilities and perform testing studies.

CEA Leti, a French government laboratory in Grenoble, France has become an important education and research partner of the Center for E^{3}S. The Center's engagement with CEA-Leti started in 2014 with an education partnership. This education partnership has continued with **Louis Hutin** (*CEA-Leti*) hosting 2015 E^{3}S REU student, **Donato Kava** (*UTEP*) as a student researcher for 9 weeks in Summer 2016. Using the supplemental funding awarded in Period 7, the Center was able to send a second student, **Imani- Kai Horton** (2015 UCB- HBCU program) to Grenoble under the supervision of **Gael Pillonnet**, a new affiliate in this period.

The Center has continued its partnership with the Graduate Division of the UC Office of the President (UCOP) to fund a research internship program for undergraduates from Historically Black Colleges and Universities, the UCB-HBCU program in Summer 2016. This program offers paid research experiences at UC Berkeley and at the HBCU home institution for a duration of 15 months. The program, which is managed by E^{3}S as an extension of the E^{3}S REU program, is partially funded by UCOP and the E^{3}S REU program.

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

The Center has continued its tradition of including Leadership Day as part of the programming of the summer internship programs. On Leadership Day, the summer undergraduate students ha the opportunity to serve as mentors to middle school students. This year, **A. Dayal**, Program yoUr Future, arranged a joint Leadership Day participation between middle school students of her program and the E^{3}S interns. All participants learned about the experiences of colleges students pursuing science and engineering majors and observed demonstration of science principles by community college students.

In Period 7, the Center engaged new partners to enhance its organized education and diversity programs.

- The Center expanded its engagement with industry partner, Lam Research. Lam provided a tour and presentation of its facilities to the Center's summer students in conjunction with the Center's Education and Diversity efforts.
- The Center provided a mentoring experience to students in the Center for Integrated Access Networks (CIAN) REU program at Berkeley. CIAN is a research center based at the University of Arizona, with faculty at Berkeley that are also E^3S faculty. As the research areas are similar, we provided the students with a cohort of fellow interns so that they had a more positive experience researching at Berkeley.

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

2b. *Outcomes and Impact*

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

2c. *Performance Against Metrics*

Metric	Targets	Results					
		P 2	P 3	P 4	P 5	P 6	P 7
Contacts with industry:							
• Talks & Meetings	All Periods: 36	66	20	42	62	35	42
• Industry Presentations	All Periods: Yearly: 2	4	2	6	3	5	2
Research collaboration with industry	Period 4: 1 Period 5: 2 Period 6: 3 Period 7: 3	0	1	1	4	6	8

2d. *Partnerships Plans for Period 8*

With recent developments in the nanophotonics and nanomechanics themes (see Research section), the Center expects increased industry engagement in Period 8. Center management and the leadership team will assist researchers in deepening the engagement level with the existing industry members, as well as recruiting additional industry members.

We expect that existing research partnerships with Lam Research, Applied Materials, and IBM will extend to Period 8, while new ones will be formed as needed. Efforts by the Squitch group are currently also underway to extend the partnership with MITLL from the current informal stage to a formal partnership.

During Summer 2017, the education partnerships are expected to continue at the same level, to ensure the best experience for the summer students. In Period 7, the Center received a NSF supplement to provide second REU internships to two targeted populations of Center's REU alumni, women and racial minorities who are majoring in Electrical Engineering. The Center plans to use this for second engagements of students, and to leverage our partnerships, including CEA-Leti, to have continued success with our education and diversity efforts.

VI. DIVERSITY

1a. Goal and Objectives

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

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, we cultivate an inclusive environment that engages, embraces, and encourages intellectual curiosity and socio-cultural development.

The Center infuses diversity and inclusion throughout it programmatic endeavors to enhance both the academic experience and the scholarly environment to prepare students to enter an increasingly complex and diverse society. Since the inception of the Center for E^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. While detailed numbers will be given below, cumulatively, 30% (19) of our REU students have been underrepresented minorities and 43% (27) female. Our TTE REU program, so far, has hosted 27 students; out of these 27 students, 8 have been females, 7 URMs, 18 first-generation, and 2 veterans.

In Period 7, the Center concentrated on further strengthening programs and initiatives to align with our goal of increasing diversity in the field of low-energy electronic devices and nurturing a diverse pool of participants in our pipeline. Additionally, the Center has continued to track past participants and provide advising, support, mentoring, and preparation for applying for transfer admission to a four-year institution or for graduate school.

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

Sustained Diversity Recruitment Initiatives: The Center has remained committed to the recruitment of graduate and undergraduate students from underrepresented groups into our programs. During this period, the Center has continued its partnership with Historically Black Colleges and Universities (HBCUs) to offer undergraduates students from HBCU institutions a summer research experience, and if eligible, a second summer experience in the E^3S REU program. The HBCU summer research experience is funded by the University of California Office of the President (UCOP). In continuation of this initiative and its partnerships, **Kedrick Perry** traveled to three HBCUs (Morgan State, University of the District of Columbia, Howard University) and graduate student **Benjamin Osoba** traveled to one (Florida A & M University) to conduct recruiting seminars and introduce the Center's research opportunities to students at

HBCUs. In meeting with faculty from all visited HBCUs and one dean, **Kedrick Perry** discussed opportunities to work more closely in the future. It is expected that continuous engagement with students and faculty from HBCUs will enhance the students' experience and preparation for graduate study at UC Berkeley and other E^{3}S schools. The UCOP award also funds faculty development workshops, in which Berkeley and HBCU faculty come together to cultivate research collaborations, discuss research interests, identify research synergies, and share projects the undergraduate researcher can work on at UC Berkeley and the HBCU home institution.

In Period 7, the Center aimed to increase diversity by participating in several recruiting events across the nation. This year, **Lea Marlor**, attended annual conferences of the Society of Women Engineers (SWE), the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS); and **Kedrick Perry** attended the conferences for the American Indian Science and Engineering Society (AISES), Society of Hispanic Professional Engineers (SHPE), University of Maryland Baltimore County McNair Scholars, and UC Berkeley McNair Scholars. At each conference, information about E^{3}S topics, summer research experiences, and graduate programs were presented to a diverse group of students. The Center has continued to incorporate topics related to inclusion and diversity awareness into the fabric of E^{3}S. At this year's annual retreat, **Kedrick Perry**, gave a presentation on cultivating a climate of inclusive excellence with touched on issues such as perception, implicit bias, microaggressions, and equity.

1b. Performance Metrics

Table 6.1

Objective	Metrics	Frequency	Targets
Diversity	Women in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 20% Period 6: 25% Period 7: 25%
	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%
	Participants from underrepresented* groups in the Center's Diversity programs	Annually	Period 3: Baseline Period 4: 80% Period 5: 85% Period 6: 85% Period 7: 85%
	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%
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate *(new)*	Annually beginning in Period 6	Period 6: 85% Period 7:85%
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering *(new)*	Annually beginning in Period 6	Period 6: 80% Period 7: 80%

1c. Problems Encountered

In Period 7, the Center is still challenged by the low 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.

The new diversity director, **Kedrick Perry**, joined the Center in June 2016. Before his appointment, the Center was without a full-time diversity director since the tragic passing of **Aimee Tabor** in December of 2015.

2a. Development of Human Resources

In Period 7, the Center has ensured that its diversity programs include a strong integration with the Center's research activities. The Center continues to partner with nationally recognized pre-college and higher education programs and has formed alliances to collectively tackle the challenge of building a diverse pipeline of students who will enter and diversify the workforce. The Center has further 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 and MIT, and program partners at Los Angeles Trade-Technical College, Mathematics Engineering Science Achievement (MESA), and Berkeley's Transfer Alliance Project (TAP) to discuss partnership opportunities.

- *Pre-college Programs*

  In Period 7, the Center continued to partner with MIT's Office of Engineering Outreach Programs (OEOP) on programs for high school seniors. These existing MIT programs promote early interest in science and engineering careers to students from underrepresented groups. The Center's main role is to promote the career path of electrical engineering and related technical fields. We do this by supporting the offering of electronics training in the MOSTEC program. Previously in the Goals and Objectives section, we shared the history of our involvement with OEOP and these remaining partnership programs that have continued to Period 7.

  Table 6.2

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**Shawna Young** (MIT) and **Lea Marlor** (Berkeley)
Intended Audience	Rising 12th grade high school students
Approx. Number of Attendees (if appl.)	Total: 43 Females: 17 (40%), URMs: 29 (67 %)

As a founding member of the MIT Online Science, Technology, and Engineering Community (MOSTEC), the role of the Center for E^3S is to provide electronics education resources. Now in its seventh year, the MOSTEC program continues to promote student interest in various fields of engineering and science and to assist them with aspects of the college application process. MOSTEC students complete online coursework and projects in science, engineering, and technical writing. In

July, MOSTEC students from all over the country gather for the MOSTEC Conference at MIT. Participants are exposed to MIT's faculty and staff who provide them with admissions and financial aid tips, lead electronics workshop, facilitate discussions about science and engineering research, and provide mentorship opportunities. After the conference, the students continue to learn more about science and engineering, interact with college faculty and staff, and receive online mentorship from undergraduates, graduate students, and industry professionals through the MOSTEC online platform.

Of our ETERNS, 82% (9) have completed a four-year degree in an E^3S related major. Five are currently enrolled in graduate school (for STEM and all at E^3S institutions). Cumulatively, 27% (3) are underrepresented minorities and 45% (5) are female.

- *Undergraduate Programs*

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

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

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

Table 6.3

Activity Name	Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU)
Led by	**Lea Marlor** (Berkeley) and **Jeff Bokor** (Berkeley)
Intended Audience	Community college students
Approx. Number of Attendees (if appl.)	Total: 5 Females: 0 (0%), URMs: 2 (40%), 3 (60%) First Gen

During summer 2016 (Period 7), E^3S at UC Berkeley hosted five of eleven community college students in the TTE REU program (TTE REU Recruitment Flyer: http://www.e3s-center.org/education/2016_TTE_Flyer.pdf). These students completed nine weeks of research in the laboratories of E^3S faculty, **Tsu-Jae King Liu** and **Jeff Bokor**; and E^3S Education Affiliates, **Jeff Clarkson** and **Alex Zettl**. Education Affiliates are not part of the Center's research team, but their research disciplines are similar to those of the Center. **Jeff Clarkson** and **Alex Zettl** joined the Center as affiliates in Period 5.

In Period 7, the TTE REU experience started with a one-week bootcamp on the fundamentals of electronics, laboratory procedures, safety training, ethics training, and software training before embarking on independent research. During the 9 weeks of hands-on independent research, the TTE REU students also attended a variety of enrichment activities and participated in weekly one-on-one mentorship meetings with **Lea Marlor.** For details on enrichment activities, see https://www.e3s-center.org/education/2016_TTE_REU_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, 96% of the Center's TTE alumni (2011-2015 cohorts) 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. These 27 students, (8 females, 7 URMs, 18 first-generation, 2 veterans) have transferred to UC Berkeley (24), UCLA (2), UC San Diego (1), and USC (1). Among this group, four of the students transferred to UC-Berkeley in Period 7, one (25%) is female, and three (75%) are first-generation. The Center is actively conducting research to determine the impact of TTE on transfer rates, self-efficacy, and graduate school matriculation rates. This project was led by **Lea Marlor**.

Summer Research Programs for Undergraduate Students from 4-Year Institutions: The Center hosts a Summer REU program at all E^{3}S affiliated schools, and this year 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), **Lea Marlor** (Berkeley), and **Eli Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx. Number of Attendees (if appl.)	Total: 11 Female: 5 (45%), URMs: 4 (36%)

The Center's 9-week E^{3}S REU program received approximately 80 applications. Eight of these students were matched with Center faculty at Berkeley and three were matched at MIT. At MIT, students were hosted by **Dimitri Antoniadis, Jesus del Alamo, and Jing Kong**. At Berkeley, students were hosted by E^{3}S faculty **Junqiao Wu**, **Sayeef Salahuddin**, **Tsu-Jae King Liu**, **Jeff Bokor**, **Eli Yablonovitch**, **Vladimir Stojanovic, Felix Fischer**, and **Vivek Subramanaian** (affiliate). In addition to research activities, students attended weekly enrichment activities that included field trips and preparation for GRE. This summer, Sandia National Labs provided the students an overview of Sandia's research technology and a tour. Each student also received one-on-one mentorship meetings with **Kedrick Perry**, the Center's Director of Diversity. For calendar of events and activities, see: https://www.e3s-center.org/education/2016_E3S_REU-Program_Calendar.pdf.

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

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

To date, 65% (41) of our E^3S REU students have completed a four-year degree in an E^3S related field. Of those, 73% (30) are enrolled in graduate school (for STEM) with 14 at an E^3S institution. Cumulatively, 30% (19) of our REU students are underrepresented minorities and 43% (27) are female.

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 7, 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^3S collaborated with UC Berkeley's College of Engineering to recruit for the Center's diversity programs, targeting students at 4-year institutions. Together, four universities were visited and six diversity conferences were.

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

For the community college programs, **Lea Marlor** visited six 2-year colleges: College of the Desert, Los Angeles Trade-Technical College, Pasadena City College, College of the Canyons, and Bakersfield College and El Camino College. The Center also supported three 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 and the Council on Undergraduate Research REU Symposium. One student has been accepted to present his research at the National Council on Undergraduate Research National Conference, and is expected to present his work during Period 8, through the support of the Center.

2b. Impact on the Center's Diversity

In Period 7, the Center has committed available resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. We believe active recruitment ensures that E^3S programs will have access to competitive candidates and highly qualified participants, regardless of race, color or gender. As a result, we are beginning to see more students from underrepresented groups pursue research in the Center or closely related science and engineering fields.

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

In summary, the Center has continued to make diversity a high priority in Period 7. 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. Performance Against Metrics

Table 6.5

Objective	Metric	Targets	Results					
			P 2	P 3	P 4	P 5	P 6	P7
Diversity	Women in the Center's research programs	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 20% Period 6: 25% Period 7: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)	19 (17%)
	Underrepresented minorities in the Center's research programs	Period 2: Baseline Period 3: 15% increase Period 4: 5% Period 5: 10% Period 6: 10% Period 7: 12%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)	14 (13%)
	Participants from underrepresented* groups in the Center's Diversity programs	Period 3: Baseline Period 4: 80% Period 5: 85% Period 6: 85% Period 7: 85%	n/a	93 (82%)	Women 37 (44%) URM: 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%)
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center *(new)*	Period 6: 40% Period 7: 45%	*(new for Period 6-10)*				17 (55%)	23 (54%)

	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate *(new)*	Period 6: 85% Period 7: 85%	*(new for Period 6-10)*	16 (70%)	22 (81%)
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering *(new)*	Period 6: 80% Period 7: 80%	*(new for Period 6-10)*	73 (55%)	102 (63%)

2d. Plans in Period 8

In Period 8, the Center will continue to be staffed with Education Manager, **Lea Marlor**, and Diversity Director, **Kedrick Perry**. E^3S will focus on maintaining and strengthening its to efforts to attract women and underrepresented minorities but also seek to gain greater traction in attracting first-generation students, low-income students, those of varying ability/disability statuses, and veterans. Perry will continue efforts to draw students from HBCUs through the activities of the UCB-HBCU program of which Theme Leader **Tsu-Jae King Liu** is the PI. **King Liu** and **Perry** have plans to host a HBCU workshop for faculty in the Spring of 2017. Perry will also begin to outline plans for a REU for the deaf and hard of hearing with potential partner Gallaudet University.

In Period 7, greater emphasis was placed on selecting electrical and electronics engineering undergraduates to ensure that when they joined a Center member institution, the students would be in a department with a choice of Center faculty to choose from as their advisors. This practice will continue in Period 8 along with the use of national databases to target prime candidates, enhancing the profile of E^3S amongst diverse undergraduates, strengthening partnerships with minority-serving institutions, and building collaborations with organizations that focus on sending diverse students to graduate school such as the federal TRIO program, McNair Scholars. Additionally, Kedrick Perry will work more closely with UTEP and FIU to enable students from these schools to intern at other E^3S schools.

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 new diversity director, **Kedrick Perry**, replacing **Aimee Tabor** (who unexpectedly passed away in December of last year) and (2) the new program coordinator, **Aine Minihane**, replacing **Fanny Li**. An additional change in the organizational structure of the Center was the addition of the diversity director and education and outreach manager positions to the Center's Executive Committee as observers. 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 Associate Director for Diversity
     - Tsu-Jae King Liu – Theme Leader and Associate Director for Education
     - Ming C. Wu – Theme Leader
     - Michael Bartl – Executive Director
     - Vladimir Bulovic – Site Head, MIT (the largest subaward institution)

     ii) Elected members:

     - H.-S. Philip Wong, Stanford
     - David Zubia, University of Texas at El Paso (UTEP)

  b) The new Executive Board was ratified at the June 22, 2016, Executive Committee meeting with 100% of the vote in favor. In addition, Diversity Director, **Kedrick Perry**, and Education and Outreach Manager, **Lea Marlor**, were added to the Executive Committee as non-voting members ("observer" status). In this status both can attend all Executive Committee meetings, propose agenda items, and participate in all discussions.

  c) The by-laws of the E^3S Executive Committee were reviewed by the Center's leadership team. No changes were recommended and the by-laws were ratified at the June 22, 2016, Executive Committee meeting with 100% of the vote in favor.

- E^3S Management and Operations Team:
  - E^3S continues to be led and managed by Executive Director, **Michael Bartl**. The executive director manages the Center's staff team, consisting of the diversity director, the education and outreach manager, the program coordinator, and various student assistants. In this period, the Center underwent a change in the program coordinator position, with **Aine Minihane**, replacing **Fanny Li**, who left the Center for a job in the private sector.
  - The Center's programmatic efforts in Education and Diversity are the responsibility of the education and outreach manager and the diversity director. After the unexpected passing of Dr. **Aimee Tabor**, the Center started a national search to fill the position of diversity director. After a 3-month search process, the Center hired Dr. **Kedrick Perry** as its new diversity director, starting in June 2016. A biosketch of Dr. Perry is given in Appendix A. As in past years, the education and diversity programs enjoy faculty support through the two associate director positions; **Jeffery Bokor** for diversity and **Tsu-Jae King Liu** for education.

1b. Table 7.1. Performance Metrics

Objective	Metrics	Frequency	Targets
Center Management	Centerwide Communications *(discontinued)*		
	Annual Surveys:		
	• Students /Postdocs	Annually	According to Likert scale: Period 2: 3 or higher Period 3: 3 or higher Period 4: 3 or higher Period 5: 3 or higher Period 6: 4 or higher Period 7: 4 or higher
	• Co-PIs	Annually beginning in Period 3	
	• External Advisory Board	Annually	
	Authorship disputes	Annually beginning in Period 3	Period 2: 20% decrease Period 3: 20% decrease Period 4: 20% decrease Period 5: 20% decrease Period 6: 0 Period 7: 0
	Plagiarism	Annually	Period 2: 0 Period 3: 0 Period 4: 0 Period 5: 0 Period 6: 0 Period 7: 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

From the inception of this Center, feedback is sought from faculty, students and postdocs in evaluating 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 funding period 2 this feedback is obtained through two annual surveys, one from the Center faculty, and another one from the student and postdocs of the Center. The surveys are conducted, administered and analyzed by our external evaluator, **Dr. Catherine Amelink**. Dr. Amelink then reports the result of the surveys (with all names and personal information removed) to the E3S leadership team

Table 7.2. Center Management Metrics Table

	Metric	Targets	Results					
			P 2	P 3	P 4	P 5	P 6	P 7
Center Management	Annual Surveys:	*Targets*	>3 on Likert Scale				>4 on Likert Scale	
	• Students /Postdocs	*Results*	Average 3.9±0.2	Average 4.0±0.3	Average 4.2±0.2	Average 4.5±0.2	Average 4.3±0.2	Average 4.3±0.3
	• Co-PIs	*Results*	No survey in Period 2	Leadership 4.46 Collaboration 3.25	Leadership 4.7±0.5 Collaboration not available	Leadership 4.9±0.1	Leadership 4.6±0.1	Leadership 4.8±0.2
	• External Advisory Board	*Results*	Strategic Plan: 4.18 Accomplishment: 4.01	Strategic Plan 4.07 Accomplish-ments: 3.96				4.8±0.4
	Authorship disputes	*Targets*	20% decrease annually				0	0
		Results	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale	0	0	0
	Plagiarism	*Targets*	0	0	0	0	0	0
		Results	0	0	0	0	0	0
	Changes in Center processes made in response to evaluation results	*Targets*	3 months for closure of regular Action; 1 week for closure of time-sensitive Action					
			(new for P6-10)		0		0	

Each year, the Center conducts two center-wide perception surveys among its members to measure the effectiveness of the Center leadership: 1) Postdocs and graduate student survey and 2) faculty survey. Both surveys are designed to assess the performance of the Center's leadership on what are considered the Center's core values: Inclusiveness, teamwork, communication, agility/decision making, performance, and ethical conduct.

2016 has been the sixth year in which the graduate students & postdocs survey has been conducted. The overall average leadership rating of 4.3 on the Likert scale (see Appendix J for points definition) indicates a very positive evaluation of the Center leadership team and the Center structure by the graduate students and postdocs.

A deeper analysis of individual responses revealed one category that showed a significant deviation in terms of Likert rating from the rest of the responses (see Appendix J). For the question "Since joining the Center I have developed a working relationship with someone in the Center who is not part of my home institution" the Likert scale response was 3.5 (in between of "Agree" and "Neutral"). While this is still considered a positive response on the Likert scale, the Center management and leadership will use this result as extra motivation to demonstrate to students and postdocs the advantages of being a multi-institutional research and education center. For example, the center leadership has initiated a multi-institutional postdoc program as well as a inter-institutional rotation program in this period.

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

	2011	2012	2013	2014	2015	**2016**
Inclusiveness	3.8	4.1	4.1	4.6	4.4	**4.3**
Teamwork	3.7	3.6	4.0	4.6	4.2	**4.2**
Open and timely communications	4.0	4.2	4.2	4.7	4.2	**4.4**
Agility/Decision Making	4.0	4.1	4.2	4.5	4.4	**4.4**
Focus on Performance	3.8	4.1	4.1	4.5	4.2	**4.2**

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

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 revealed that the Center faculty view the Center leadership very positively, as indicated by an overall average leadership rating of 4.8 on the Likert scale. The detailed responses to leadership questions are given in Appendix K. In addition, all faculty respondents answered the question "*I feel that my E^3S colleagues act in an ethical manner*" with YES.

1d. Problems Encountered

Due to **Dr. Tabor's** (diversity director) unexpected passing, the Center was without a diversity director until the middle of June. This caused some delays in implementing our online education legacy plans such as the Nanohub website and the E^3S eBook (see also Section 3). Furthermore, our student recruiting activities in the spring were moved to the fall and we postponed the annual meeting of the Center's Education Working Group (with selected members of the E^3S External Advisory Board). With the onboarding of our new diversity director, all of the delayed recruiting and education activities are now underway and we tentatively scheduled the Center's Education Working Group meeting for February 2017.

2. Management and Communications Systems

Management: The main discussion and decision making vehicle of the E^3S Executive Committee are six meetings throughout the funding period. Due to the multi-institutional composition of the Executive Committee, these meetings are held through remote participation of non-Berkeley executive committee members via Webex. So far, the Executive Committee met five times in 2016; a sixth meeting is scheduled for December 13 (see details below).

Table 7.3. Executive Committee Meetings – Period 7	
Meeting Dates	**Agenda Topics**
March 17, 2016	Review of Data Management Plan; Site Visit Recommendations; Budget Discussion; External Advisory Board Membership Review
May 11, 2016	Review of Period 7 Budget; Annual Retreat Planning
June 22, 2016	Review and Ratification of By-Laws; Approval of External Advisory Board Membership; External Advisory Board Meeting Planning
September 16, 2016	Debrief of Annual Retreat; Proposal Review Planning; Reverse Site Visit Agenda Discussion
October 27, 2016	Center-wide Annual Proposal Review
December 13, 2016 *(scheduled)*	Review of the Center's results versus the Strategic Plan; Review of Preliminary Feedback from External Advisory Board; Reverse Site Visit Planning

The annual review of all proposed Period 8 research programs in the Center was performed by the Executive Committee in October. Final discussions and votes were held during the October 27 Executive Committee meeting. Guidance for both the Center investigators (proposers) and the Executive Committee members (reviewers) was the Centers Strategic Plan. The review and voting process ended with unanimous agreement on all the proposed programs and faculty member changes as reported in this Annual Report.

Communications and Planning: The center-wide Annual Retreat remains the prime gathering and planning event for all Center faculty, students, postdocs and staff. During this event, which was held this year on September 15 and 16 at UC Berkeley, all research, education and diversity programs as well as management are reviewed with respect to progress towards the main Center goals. The theme for this year's retreat was *Inclusivity and Participation*. The retreat included research presentations from faculty, students and postdocs, representing all E^3S Themes as well as System Integration. These presentations are held on the first day of the retreat (see also retreat agenda, given as Appendix I) for which we also welcomed members from our industry partners: Intel (Ian Young, Uygar Avci), IBM (Siyu Koswatta), Applied Materials (Kim Namsung), Lam Research (Nerissa Draeger). Furthermore, the retreat provided opportunities for presentations about education and diversity achievements and plans, reports by the executive director on Center management and center-wide output, and a diversity training/workshop (including breakout sessions) by our new diversity director, Kedrick Perry. The retreat concluded with two parallel sessions: a planning and discussion meeting for faculty, and an etiquette workshop and lab tours for students and postdocs.

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.

3. *Internal and External Advisory Bodies*

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

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

- Chair: one 2-year term
- Members: one 3-year term to be followed by, at the discretion of the E^{3}S Executive Committee, additional 2-year appointments.

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

The current members of the E3S External Advisory Board are:

Table 7.4. Center for E3S External Advisory Board

Member	Affiliation	Research	Education	Diversity	Knowledge Transfer	Center Management
Samuel Bader	Argonne National Lab	x			x	x
Eun-Woo Chang	Mercer County Community College		x	x		x
Paolo Gargini	International Technology Roadmap for Semiconductors (ITRS)	x			x	
Katherine Dunphy-Guzman	Sandia		x	x		
Jonathan Heritage	UC Davis	x	x	x		
Daniel Radack	Institute for Defense Analysis (IDA)	x			x	x
Elsa Garmire	Dartmouth College	x	x	x		x
Diane Rover	Iowa State U.		x	x		x

Changes from last funding period: In 2016, two external advisors, **Mark Pinto** (*Blue Danube Labs*) and **Peter Delfyette** (*University of Central Florida*) completed their 3 year terms. Both were thanked for their excellent service to the Center and were excused from the External Advisory Board. The Executive Committee approached **Thomas Theis** (*Columbia University*) to join the External Advisory Board. Prof. Theis, who just moved to Columbia University as new executive director of the Columbia Nano Initiative, agreed to serve on the External Advisory Board but asked to delay his start date to March 2017. The Executive Committee agreed to this start date in a unanimous vote.

A subset of External Advisors functions as the *Education Working Group* to advise and guide the Center's education and diversity programs. It is important to note that the Education Working Group, chaired by **D. Rover** (*Iowa State*), does not assess the education and diversity programs—this is done as part of the annual evaluation by the entire External Advisory Board. As mentioned above, due to the change in the Center's diversity director position and the delayed start of the new diversity director, the next meeting of this advisory body has been moved to spring of 2017.

The annual meeting of the E^3S External Advisory Board took place on October 13 (the agenda is given in Appendix C). The main purpose of these annual meeting is update the External Advisory Board on the Center's progress in research, education, diversity, knowledge transfer, and center management, and to receive feedback and input from the members of this important advisory body.

All current members of the External Advisory Board participated in this year's meeting. The full list of attendees was:

- Paolo Gargini, ITRS (*Chair*)
- Samuel Bader, Argonne National Lab
- Eun-Woo Chang, Mercer County Community College
- Katherine Dunphy-Guzman, Sandia
- Elsa Garmire, Dartmouth College
- Jonathan Heritage, UC Davis
- Daniel Radack, IDA *(participate remotely via Webex)*
- Diane Rover, Iowa State University

Following the presentations by E^3S faculty, postdocs, students, and staff, the External Advisory Board members deliberated and started work on their written report to the Center. The meeting concluded with an oral feedback by all members, providing supportive comments, particularly with respect to the research progress, the student and postdoc speakers and poster presenters, and the new education and diversity initiatives. The written report will be provided by Chair **Gargini** and we expect this report to be made available before the upcoming NSF Reverse Site Visit.

Industrial Research Board: As in previous years, the Center continued to enjoy close relationship with leaders in the semiconductor industry that have expressed their intention to collaborate with the Center for E^3S, forming the Industrial Research Board. These collaborations are documented through letters from these companies and their representatives (see below) to the UC Berkeley Vice Chancellor of Research Office. These letters of collaboration not only included interest in participating in research, but in some cases also financial support, in kind and otherwise, and non-financial support of E^3S activities. The current members of the Center for E^3S Industrial Research Board are:

Company	**Main Contact**
Lam Research	David Hemker
IBM	Ghavam Shahidi
Hewlett-Packard	Stan Williams
Applied Materials	Ellie Yeh
Intel	Ian Young

The Industrial Research Board is an integral part of our Center. It monitors, advises and participates in the Center's research. To underline the research participation, this year the Center published a collaborative paper in the Journal of Applied Physics [120, 084507 (2016)] titled "Auger generation as an intrinsic limit to tunneling field-effect transistor performance" with E^3S co-authors from Berkeley, MIT, and IBM.

The fact that industry partners are part of the Center for E^3S is also exemplified in their participation in Day 1 activities of the Annual Center Retreat (see agenda given as Appendix I) at UC Berkeley. Day 1 of the annual retreat covered all research presentations as well as a poster session and award dinner.

The industry partners in attendance at the annual retreat were:

- Nerissa Draeger, Lam Research
- Namsung Kim, Applied Materials
- Ian Young and Uygar Avci, Intel
- Siyuranga Koswatta, IBM

Unfortunately, Dr. Stan Williams from HP Enterprise cancelled his participation the day before the retreat.

All industry partners in attendance participated actively in discussions and analyses of research results. In addition, as in previous years, the Industrial Research Board members met for deliberations at the end of the presentations and provided feedback to the Center's leadership team in a closed session. Here, detailed comments on each of the research themes was provided and suggestions were made in terms of potential transfer of results and processes to industry.

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 *(Chronological)*

1. K. Kato, **V. Stojanović**, and **T.-J. King Liu**, "Non-Volatile Nano-Electro-Mechanical Memory for Energy-Efficient Data Searching," *IEEE Electron Device Lett.*, vol. 37, no. 1, pp. 31-34, Jan 2016.
2. T. Roy, M. Tosun, M. Hettick, G.H. Ahn, C. Hu, and **A. Javey**, "2D-2D Tunneling Field-Effect Transistors Using WSe2/SnSe2 Heterostructures," *Appl. Phys. Lett.*, vol. 108, pp. 083111, Feb 2016.
3. J. Hong, B. Lambson, S. Dhuey, and **J. Bokor**, "Experimental test of Landauer's principle in single-bit operations on nanomagnetic memory bits," *Sci. Adv.*, vol. 2, no. 3, pp. 1501492, Mar 2016.
4. J. Lin, **D.A. Antoniadis**, and **J.A. del Alamo**, "InGaAs Quantum-Well MOSFET Arrays for Nanometer-Scale Ohmic Contact Characterization," *IEEE Trans. Electron Dev.*, vol. 63, no. 3, pp. 1020-1026, Mar 2016.
5. J. Lin, Y. Wu, **J.A. del Alamo**, and **D.A. Antoniadis**, "Analysis of Resistance and Mobility in InGaAs Quantum-Well MOSFETs from Ballistic to Diffusive Regimes," *IEEE Trans. Electron Dev.*, vol. 63, no. 4, pp. 1464-1470, Apr 2016.
6. J. Lin, X. Cai, Y. Wu, **D.A. Antoniadis**, and **J.A. del Alamo**, "Record Maximum Transconductance of 3.45 mS.um for III-V FETs," *IEEE Electron Device Lett.*, vol. 37, no. 4, pp. 381-384, Apr 2016.
7. Y. Kang, **J. Bokor**, and **V. Stojanovic**, "Design Requirements for a Spintronic MTJ Logic Device for Pipelined Logic Applications," *IEEE Trans. Electron Dev.*, vol. 63, no. 4, pp. 1754-1761, Apr 2016.
8. E. M. Sletten and **T. M. Swager**, "Readily Accessible Multifunctional Fluorous Emulsions," *Chem. Sci*, vol. 7, pp. 5091-5097, Apr 2016.
9. M. Amani, R. A. Burke, X. Ji, P. Zhao, D.-H. Lien, P. Taheri, G. H. Ahn, D. Kiriya, J. W. Ager, **E. Yablonovitch**, J. Kong, M. Dubey, and **A. Javey**, "High Luminescence Efficiency in MoS2 Grown by Chemical Vapor Deposition," *ACS Nano.*, vol. 10, no.7, pp. 6535 -6541, Jun 2016.
10. J. Hong, A. Hadjikhani, M. Stone, P. Liang, F. Allen, V. Safonov, **J. Bokor**, and **S. Khizroev**, "The Physics of Spin-transfer Torque Switching in Magnetic Tunneling Junctions in Sub-10-nm Size Range," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1-4, Jul 2016.
11. C. Heidelberger and **E.A. Fitzgerald**, "Heavy P-Type Carbon Doping of MOCVD GaAsP Using CBRCl3," *J. Cryst. Growth*, vol. 446, pp. 7–11, Jul 2016.
12. J. Gorchon, Y. Yang, and **J. Bokor**, "Model for multishot all-thermal all-optical switching in ferromagnets," *Phys. Rev. B*, vol. 94, no.2, pp. 020409, Jul 2016.
13. J. Lin, L. Czornomaz, N. Daix, **D.A. Antoniadis**, and **J.A. del Alamo**, "Ultrathin Body InGaAs MOSFETs on III-V-On-Insulator Integrated with Silicon Active Substrate (III-V-OIAS)," *IEEE Trans. Electron Dev.,* vol. 63, no. 8, pp. 3088-3095, Aug 2016.
14. J.T. Teherani, S. Agarwal, W. Chern, P.M. Solomon, **E. Yablonovitch**, and **D.A. Antoniadis**, "Auger Generation as an Intrinsic Limit to Tunneling Field-Effect Transistor Performance," *J. Appl. Phys.*, vol. 120, no. 8, pp. 084507, Aug 2016.

15. T. Marangoni T, D. Haberer, D.J. Rizzo, R.R. Cloke, and **F.R. Fischer**, "Heterostructures through Divergent Edge Reconstruction in Nitrogen-Doped Segmented Graphene Nanoribbons," *Chem. Eur. J.*, vol. 22, no. 37, pp. 13037-13040, Aug 2016.
16. **J.A. del Alamo**, **D.A. Antoniadis**, J. Lin, W. Lu, A. Vardi, and X. Zhao, "Nanometer-Scale III-V MOSFETs," *IEEE J. Electron Devices Soc.*, vol. 4, no. 5, Sept 2016.
17. W. S. Ko, I. Bhattacharya, T-T. D. Tran, K. W. Ng, S. Gerke, and **C. Chang-Hasnain**, "Ultrahigh Responsivity-Bandwidth Product in a Compact InP Nanopillar Phototransistor Directly Grown on Silicon," *Sci. Rep.*, vol. 6, no. 33368, Sept 2016.
18. A. Vardi and **J.A. del Alamo**, "Sub-10 nm fin-width self-aligned InGaAs FinFETs," *IEEE Electron Device Lett.*, vol. 37, no. 9, pp. 1104-1107, Sept 2016.
19. S.B. Desai, S.R. Madhvapathy, A.B. Sachid, J.P. Llinas, Q. Wang, G.H. Ahn, G. Pitner, M.J. Kim, **J. Bokor**, C. Hu, **H.-S.P. Wong**, and **A. Javey**, "MoS2 transistors with 1-nanometer gate lengths," *Science*, vol. 354, no. 6308, pp. 99-102, Oct 2016.
20. R. Sajjad, W. Chern, **J.L. Hoyt**, and **D.A. Antoniadis**, "Trap Assisted Tunneling and Its Effect on Subthreshold Swing of Tunnel FETs," *IEEE Trans. Electron Dev.*, vol. 63, no. 11, pp. 4380-4387, Nov 2016.
21. J. Gorchon, R. B. Wilson, Y. Yang, A. Pattabi, J. Y. Chen, L. He, J. P. Wang, M. Li, and **J. Bokor**, "Role of electron and phonon temperatures in the helicity-independent all-optical switching of GdFeCo," *Phys. Rev. B,* vol. 94, no. 18, pp. 184406, Nov 2016.
22. K. Kato, **V. Stojanović**, and **T.-J. King Liu**, "Embedded nano-electro- mechanical memory for energy-efficient reconfigurable logic," *IEEE Electron Device Lett.*, vol. 37, no. 12, pp. 1563-1565, Dec 2016.
23. W.J. Ong, F. Bertani, E. Dalcanale, and **T.M. Swager**, "Redox Switchable Thianthrene-Cavitands," *Synthesis*, vol. 49, no. 2, pp. 358-364, Jan 2017.
24. P. Zheng, S.W. Kim, D. Connelly, K. Kato, F. Ding, L. Rubin, and **T.-J. King Liu**, "Sub-lithographic patterning via tilted ion implantation for scaling beyond the 7 nm technology node," *IEEE Trans. Electron Dev.*, vol. 64, no. 1, pp. 231-236, Jan 2017.
25. Y. He, S. Savagatrup, L.D. Zarzar, and **T.M. Swager**, "Interfacial Polymerization on Dynamic Complex Colloids: Creating Stabilized Janus Droplets," *ACS Appl. Mater. Interfaces*, vol. 9, pp. Jan 2017.
26. C. Heidelberger and **E. Fitzgerald**, "GaAsP/InGaP heterojunction bipolar transistors grown by MOCVD," J. Appl. Phys., vol. 121, no. 4, pp. 045703, Jan 2017
27. G.N. Malheiros-Silveira, I. Bhattacharya, S.V. Deshpande, D. Skuridina, F. Lu, and **C.J. Chang-Hasnain**, "Room-temperature Fabry-Perot resonances in suspended InGaAs/InP quantum-well nanopillars on a silicon substrate," *Opt. Express*, vol. 25, no. 1, pp. 271-277, Jan 2017.
28. K.T. Settaluri, C. Lalau-Keraly, **E. Yablonovitch**, and **V. Stojanović**, "First Principles Optimization of Opto-Electronic Communication Links," *IEEE Trans. Circuits Syst. I*, published online (doi: 10.1109/TCSI.2016.2633942), Jan 2017.
29. C. Qian, A. Peschot, B. Osoba, and **T.-J. King Liu**, "Sub-100 mV computing with electro-mechanical relays," *IEEE Transactions on Electron Devices*, published online (doi: 10.1109/TED.2017.2657554), Feb 2017.

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

1. S. Almeida, A. Vidaña, and **D. Zubia**, "Conductance Modulation in 2D Materials by NEMS for Lower-Power Applications," submitted to *Semicond. Sci. Technol.* (2017).

2. S. Deshpande, I. Bhattacharya, G. Malheiros-Silveira, K.W. Ng, F. Schuster, W. Mantei, K. Cook, and **C. Chang-Hasnain**, "Bright 1.5 µm nano-LEDs on silicon using position-controlled InP nanopillars," submitted to *ACS Photonics* (2017).
3. W. Lu, X. Zhao, D. Choi, S. El Kazzi, and **J.A. del Alamo**, "Alcohol-Based Digital Etch for Sub-10 nm III-V Multigate MOSFETs," submitted to *IEEE Electron Device Letters* (2017).
4. B. Saha, A. Peschot, B. Osoba, **T.-J. King Liu**, and **J. Wu**, "Reduction of Adhesion Energy in NEM Relay Metals Through Surface Engineering," submitted (2016).
5. F. Schuster, J. Kapraun, G.N. Malheiros-Silveira, S. Deshpande, and **C.J. Chang-Hasnain**, "Site-Controlled Growth of Monolithic InGaAs/InP Quantum Well Nanopillar Lasers on Silicon," submitted to *Nano Lett.* (2017).
6. R.B. Wilson, J. Gorchon, C.-H. Lambert, Y. Yang, **S. Salahuddin**, and **J. Bokor**, "Ultrafast magnetic switching of GdFeCo with electronic heat currents," submitted (2016).
7. R.B. Wilson, Y. Yang, J. Gorchon, C.-H. Lambert, **S. Salahuddin**, and **J. Bokor**, "Electric Current Induced Ultrafast Demagnetization," submitted (2016).
8. Y. Yang, R.B. Wilson, J. Gorchon, C.-H. Lambert, **S. Salahuddin**, and **J. Bokor**, "Ultrafast Magnetization Reversal by Picosecond Electrical Pulses," submitted (2016).
9. X. Zhao, C. Heidelberger, **E.A. Fitzgerald**, and **J.A. del Alamo**, "Source/Drain Asymmetry in InGaAs Vertical Nanowire MOSFETs," submitted to *IEEE Transactions on Electron Devices* (2017).
10. X. Zhao, A. Vardi, and **J.A. del Alamo**, "Sub-thermal Subthreshold Characteristics in Top-down InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs," submitted to *IEEE Electron Device Letters* (2017).

<u>Conference Proceedings </u>(Chronological)

1. S. A. Fortuna, C. Heidelberger, K. Messer, K. Han, E.A. Fitzgerald, E. Yablonovitch, and M.C. Wu, "Optical Antenna Enhanced Spontaneous Emission Rate in Electrically Injected Nanoscale III-V LED," *International Semiconductor Laser Conference,* May 2016.
2. I. Bhattacharya, S. Deshpande, G. N. Malheiros-Silveira, and C. Chang-Hasnain, "Efficient Electroluminescence from III/V Quantum-Well-in-Nanopillar Light Emitting Diodes Grown on Silicon," *CLEO*, May 2016.
3. I. Bhattacharya, F. Lu, G. N. Malheiros-Silveira, S. Deshpande, K. Ng, and C. Chang-Hasnain, "Room-Temperature InGaAs/InP Quantum-Well-in-Nanopillar Laser Directly Grown on Silicon," *CLEO*, May 2016.
4. K. Han, F. I. Allen, and M. C. Wu, "Helium-Ion Milling of Gold Slot Antennas," *CLEO*, May 2016.
5. K. Li, Y. Rao, C. Chase, W. Yang, and C. Chang-Hasnain, "Beam-Shaping Single-Mode VCSEL with A High-Contrast Grating Mirror," *CLEO*, May 2016.
6. G. N. Malheiros-Silveira, F. Lu, I. Bhattacharya, T. D. Tran, H. Sun, and C. Chang-Hasnain, "Integration of III-V Nanopillar Resonator to In-Plane Silicon Waveguides," *CLEO*, May 2016.
7. Ming C. Wu, "Optical Antennas Make Fast LEDs," *60th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication,* May 2016 (Invited).
8. R.N. Sajjad and D.A. Antoniadis, "A compact model for tunnel FET for all operation regimes including trap assisted tunneling," *74th Annual Device Research Conference*, Jun 2016.
9. A. Vardi, J. Lin, W. Lu, X. Zhao, and J.A. del Alamo, "High Aspect Ratio InGaAs FinFETs with sub-20 nm fin Width," *VLSI Technology Symposium*, Jun 2016.

10. X. Zhao and J. A. del Alamo, “Source/Drain Asymmetry in InGaAs Vertical nanowire MOSFETs,” *TECHCON 2016*, Sept 2016.
11. K. Kato, V. Stojanović, and T-J. King Liu, “Embedded Nano-Electro-Mechanical Memory for Reconfigurable Lookup Tables,” *International Conference on Solid State Devices and Materials*, Sept 2016.
12. K. Han, M. Amani, G.H. Ahn, K. Yu, E. Yablonovitch, A. Javey, and M.C. Wu, “WSe2 light-emitting diode coupled to optical bowtie antennas,” *21st Microoptics Conference*, Oct 2016.
13. R. Pandey, C. Schulte-Braucks, R. N. Sajjad, M. Barth, R. Ghosh, B. Grisafe, P. Sharma, N. von den Driesch, A. Vohra, B. Rayner, R. Loo, S. Mantl, D. Buca, C-C. Yeh, C-H. Wu, W. Tsai, D. Antoniadis, and S. Datta, "Performance Benchmarking of p-type In0.65Ga0.35As/GaAs0.4Sb0.6 and Ge/Ge0.93Sn0.07 Hetero-junction Tunnel FETs for Low Voltage Logic,” *International Electron Devices Meeting*, Dec 2016.
14. B. Saha, A. Peschot, B. Osoba, C. Ko, T.-J. K. Liu, and J. Wu, “Reduction of contact adhesion energy in NEM relays by ion-beam synthesized oxide nanolayers,” *Fall MRS Meeting,* Dec 2016.
15. A. Vardi, X. Zhao, and J.A. del Alamo, “Quantum-Size Effects in Sub 10 nm Fin Width InGaAs FinFETs,” *IEEE IEDM*, Dec 2016.
16. B. Osoba, B. Saha, L. Dougherty, J. Edgington, C. Qian, F. Niroui, J.H. Lang, V. Bulovic, J. Wu, and T.-J. King Liu, “Sub-50 mV NEM Relay Operation Enabled by Self-Assembled Molecular Coating,” *IEEE International Electron Devices Meeting*, Dec 2016.
17. J. Bokor, R. Wilson, J. Gorchon, Y. Yang, C.-H. Lambert, A. Pattabi, S. Salahuddin, J. Y. Chen, L. He, J.P. Wang, and M. Li, “Ultrafast charge current induced magnetization reversal in only 10 psec,” *14th RIEC International Workshop on Spintronics*, Tohoku, Japan, Dec 2016.
18. F. Niroui, M. Saravanapavanantham, T. M. Swager, J. H. Lang, and V. Bulovic, “Fabrication of nanoscale structures with nanometer resolution and surface uniformity,” *IEEE MEMS Workshop*, Jan 2017.
19. T.-J. K. Liu, U. Sikder, K. Kato, and V. Stojanović, ”There's Plenty of Room at the Top,” *30th IEEE Conference on Micro Electro Mechanical Systems (MEMS 2017)*, Jan 2017.

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

<u>*To Be Published*</u>

1. N/A

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

1. **J. A. del Alamo**, A. Vardi, and X. Zhao, “InGaAs FinFETs for future CMOS.” Invited Paper, *Compound Semiconductor Magazine*, pp. 22-26, September 2016.

1b. Conference Presentations (Chronological)

<u>Talks:</u> *(does not include Period 7 talks that have published proceedings by 2/28/2017; see p116.)*

1. S. W. Kim, P. Zheng, K. Kato, L. Rubin, and T.-J. K. Liu, “Enhanced Patterning by Tilted Ion Implantation,” *SPIE Advanced Lithography Conference*, March 2016.

2. A. Javey, "Defect Passivation, Chemical Doping, Heterostructures and Devices of Layered Semiconductors," (Invited) *MRS Spring Meeting*, NT4.6.01, March 2016.
3. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Dozententagung, German Chemical Society*, Heidelberg, Germany, March 2016.
4. F. Niroui, E. M. Sletten, T. M. Swager, J. H. Lang, and V. Bulović, "Compressive molecular films for tunneling nanoelectromechanical switches," *Podium Presentation, Materials Research Society Conference*, Phoenix, AZ, March 28 – April 1, 2016.
5. A. Javey, "(Invited) 2D Semiconductor Electronics: Advances, Challenges, and Opportunities,"*229th Electrochemical Society Meeting*, H03-1292, May 2016.
6. A. Javey, "Tutorial: 2D Layered Semiconductors: From Material Properties to Device Applications," *Graphene and Beyond*, May 2016.
7. J. A. del Alamo, "Nanoscale III-V CMOS." Invited Tutorial at *SEMI Advanced Semiconductor Manufacturing Conference (ASMC)*, Saratoga Spring, NY, May 2016.
8. H.-S. P. Wong, "Device Technologies for the N3XT 1,000X Improvement in Computing Performance," keynote speaker, *Architecture 2030 Workshop @ ISCA 2016,* June 2016.
9. E. Yablonovich, "Why We Need to Replace the Transistor, and What Would be the Newly Required Material Properties?," *17th International Laser Optics; NanoStructures for Photonics*, Saint Petersburg, Russia, June 27, 2016.
10. E. Yablonovich, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?" *24th International Symposium; NanoStructures: Physics & Technology, Plenary*, Saint Petersburg, Russia, July 1, 2016.
11. E. Yablonovich, "Another Challenge to the Ideal "Energy Filtering" t-FET: Conductance is Intrinsically Handicapped," *ESSDERC/EPFL Steep Transistors Workshop*, Lausanne, Switzerland, September 11, 2016.
12. K. Kato, V. Stojanović, and T-J. King Liu, "Embedded Nano-Electro-Mechanical Memory for Reconfigurable Lookup Tables," in proceedings of *International Conference on Solid State Devices and Materials*, September 2016.
13. H.-S. P. Wong, "Computing Performance: The N3XT 1,000X," invited talk, *JSPS165 International Symposium on Device Technology for Next-Generation Computing,* University of Tokyo, September 2016.
14. K. Kato, V. Stojanović, and T.-J. K. Liu, "Embedded nano-electro-mechanical memory for reconfigurable lookup tables," presented, *International Conference on Solid State Devices and Materials*, Tsukuba, Japan, September 2016.
15. J. Bokor, R. Wilson, J. Gorchon, Y. Yang, A. Pattabi, C.-H. Lambert,Salahuddin, J. Y. Chen, L. He, J.P. Wang, and M. Li, "Progress toward ultrafast all-electrical magnetic switching," (Invited) *International Workshop on Spin Transport*, Nancy, France, September 2016.
16. J. Hong, G. Chen, A. N'Diaye, E. Arenholz, A. Schmid, and J. Bokor, "Magnetism in a single-layer graphene grown on bcc Fe (111)," *10th LEEM/PEEM workshop*, Monterey, CA, September 2016.
17. X. Zhao, A. Vardi, and J. A. del Alamo, "InGaAs/InAlAs Heterojunction Vertical Nanowire Tunnel FETs Fabricated by a Top-down Approach," *Steep Transistor Workshop,* University of Notre Dame, October 2016.
18. J. Kong, "Two dimensional transition metal dichalcogenide materials through chemical vapor deposition synthesis," invited talk, *MRS Fall 2016*, Boston, November 27, 2016.
19. R. Wilson, Y. Yang, J. Gorchon, C.-H.A. Lambert, S. Salahuddin, and J. Bokor, "Electric Current Induced Ultrafast Demagnetization," *61st Annual Conference on Magnetism and Magnetic Materials*, New Orleans, LA, November 2016.

20. R. Wilson, J. Gorchon, C.-H.A. Lambert, Y. Yang, S. Salahuddin, and J. Bokor, "Ultrafast Magnetic Switching of GdFeCo via Electronic Heat Currents," *61st Annual Conference on Magnetism and Magnetic Materials*, New Orleans, LA, November 2016
21. J. Gorchon, Y. Yang, and J. Bokor, "Model for multi-shot all-thermal all-optical switching in ferromagnets," *61st Annual Conference on Magnetism and Magnetic Materials*, New Orleans, LA, November 2016
22. Y. Yang, J. Gorchon, C.-H.A. Lambert, R. Wilson, S. Salahuddin, and J. Bokor, "Single-shot All-Optical Switching of ferromagnetic films," *61st Annual Conference on Magnetism and Magnetic Materials*, New Orleans, LA, November 2016.
23. J. Hong, O.-J. Lee, S. Salahuddin, and J. Bokor, "Probe-based Spin Torque Transfer Device for Writing Hard Disks," *61st Annual Conference on Magnetism and Magnetic Materials*, New Orleans, LA, November 2016.
24. F. Niroui, M. Saravanapavanantham, T. M. Swager, J. H. Lang, and V. Bulović, "Self-assembly for active plasmonic devices," *Podium Presentation, Materials Research Society Conference*, Boston, Nov 2016.

<u>Accepted Posters</u>

1. J. Cao, "Nano-Electro-Mechanical Relays Using 2-Dimensional Nanomaterials for Low Energy Contacts," *E3S 2016 NSF Site Visit*, January 2016.
2. C. Heidelberger and E. A. Fitzgerald, "III-V and Group IV Materials and Integration for Energy Efficient Optical Links," *MTL Annual Research Conference*, January 21, 2016
3. B. Saha, B. Osoba, T.-J. K. Liu and J. Wu, "Surface material engineering of micro-relay electrode metals," *2016 IEEE S3S Conference*, October 11, 2016.
4. S. A. Fortuna, C. Heidelberger, K. Messer, K. Han, E.A. Fitzgerald, E. Yablonovitch, M.C. Wu, "Fast nanoscale LEDs for on-chip optical communication," *IEEE SOI-3D-Subthreshold Microelectronics Technology Unified Conference*, 2016.
5. K. Han, F. I. Allen, and M. C. Wu, "Helium-Ion Milling of Gold Slot Antennas," *CLEO: Science and Innovations 2016,* June 2016.
6. K. Han, M. Amani, G.H. Ahn, K. Yu, E. Yablonovitch, A. Javey, M. C. Wu, "WSe2 light-emitting diode coupled to optical bowtie antennas," *21st Microoptics Conference (MOC'16)*, October 2016.
7. M.C. Wu, "Optical Antennas Make Fast LEDs" *60th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN)*, May 2016 (Invited).

1c. Other Dissemination Activities (in chronological order)

1. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Department of Chemistry Seminar*, Swiss Federal Institute of Technology, Zurich, Switzerland, March 8, 2016.
2. E. Yablonovitch, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?," *IBM Research Distinguished Lecture*, Yorktown Heights, NY, March 10, 2016.

3. E. Yablonovich, "Reinventing the Circuit Board: New Technologies for Short-Distance Optical Communication," *OFC Symposium on Technologies That Will Shape the Future of Fibre Communications*, Anaheim, CA, March 21, 2016.
4. T.J. King Liu, "Device Challenges and Opportunities," *DOE Workshop on Energy Efficient Electronics*, Lawrence Berkeley National Laboratory, Berkeley, CA, March 24, 2016.
5. T.J. King Liu, "Mechanical Computing Redux for the Internet of Things," *CITRIS Research Exchange Seminar*, University of California, Berkeley, CA, March 30, 2016.
6. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Department of Chemistry Seminar*, University of California, San Diego, April 2016.
7. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Department of Chemistry Seminar*, California Institute of Technology, April 2016.
8. E. Yablonovich, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?," *290K Condensed Matter Physics Seminar*, UC Berkeley Physics Dept., April 11, 2016.
9. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Department of Chemistry Seminar*, Cornell University, May 2016.
10. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Max-Planck Institute for Carbon Research*, Mulheim, May 2016.
11. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Department of Chemistry Seminar*, Technical University of Dresden, May 2016.
12. F. Fischer, "Teaching Polymers the Meaning of Life & Nanographene Quantum Confinement," *Department of Chemistry Seminar*, Technical University of Braunschweig, May 2016.
13. E. Yablonovich, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?," *Condensed Matter Physics Seminar*, Stanford University, CA, May 19, 2016.
14. E. Yablonovich, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?," *Emerging Technologies Comm-Micro-Opto-Sensors Plenary*, Montreal, Quebec, May 26, 2016.
15. E. Yablonovich, "The Scientific Challenge of Replacing the Transistor with a Lower Voltage Device," *Address to the new E3S Summer Students*, Berkeley, CA, June 15, 2016.
16. E. Yablonovich, "Silicon Photonics Interconnects for Large-Scale Data Centers," *Berkeley Emerging Technologies Research Center Lecture*, Fremont, CA, June 20, 2016.
17. E. Yablonovich, "Optical Antennas: Spontaneous Emission Faster than Stimulated Emission," *International Summer School: Nanostructures for Photonics*, Peterhof, Russia, June 29, 2016.
18. J. A. del Alamo, "Nanoscale III-V CMOS," Korea Institute for Science and Technology, Seoul, Korea, June 30, 2016.
19. J. A. del Alamo, "Nanoscale III-V CMOS," Samsung Electronics, Seoul, Korea, July 1, 2016.
20. J. A. del Alamo, "Nanoscale III-V CMOS," *IEEE Electron Devices Society* Webinar, July 13, 2016.
21. H.-S. P. Wong, "Computing Performance: The N3XT 1,000X," *Faculty of Engineering Seminar*, The Chinese University of Hong Kong, Hong Kong. July 26, 2016.
22. T.J. King Liu, "There's Plenty of Room at the Bottom – and at the Top," *San Francisco Bay Area Nanotechnology Seminar*, Santa Clara, CA, August 16, 2016.

23. E. Yablonovich, "Energy Efficient Electronics Science: A Multi-Faceted Education and Research Program at the Center for E3S," *STC Directors Meeting*, Arlington, VA, August 24, 2016.
24. J. A. del Alamo, "Nanoscale III-V CMOS," Samsung Strategy and Innovation Center, San Jose, CA, Sept. 16, 2016.
25. E. Yablonovich, "The Scientific Challenge of Replacing the Transistor with a Lower Voltage Device," *Bipolar/Bicmos Circuits & Technology Meeting*, New Brunswick, NJ, September 26, 2016.
26. T.J. King Liu, "There's Plenty of Room at the Bottom – and at the Top," Synopsys, Inc., Sunnyvale, CA, October 18, 2016.
27. J. A. del Alamo, "Nanoscale III-V CMOS," ST Microelectronics Distinguished Lecture, Online, Oct. 20, 2016.
28. J. A. del Alamo, "Nanoscale III-V CMOS," Applied Materials, Santa Clara, CA, Oct. 24, 2016.
29. J. A. del Alamo, "Nanoscale III-V CMOS," Synopsis, Mountain View, CA, Oct. 25, 2016.
30. J. A. del Alamo, "Nanoscale III-V CMOS," Lam Research, Fremont, CA, Oct. 25, 2016.
31. H.-S. P. Wong, "Device Technologies for the N3XT 1,000X Improvement in Computing Performance," invited seminar, Zhejiang University, China.
32. H.-S. P. Wong, "Translating Nanodevices into Nanosystems: The N3XT 1,000X," *Munushian Lecture Series*, University of Southern California, CA, November 4, 2016.
33. J. A. del Alamo, "III-V FinFETs and Vertical Nanowire FETs." IMEC, Leuven, Belgium, Nov. 7, 2016.
34. H.-S. P. Wong, "Device Technologies for the N3XT 1,000X Improvement in Computing Performance," invited seminar, Microsoft Research, Seattle, WA. November 11, 2016.
35. J. A. del Alamo, "Nanoscale III-V CMOS," TSMC, Hsinchu, Taiwan, Dec. 16, 2016.
36. J. A. del Alamo, "Nanoscale III-V CMOS," National Chiao Tung University, Hsinchu, Taiwan, Dec. 16, 2016.

2. *Awards & Honors (in chronological order)*

Recipient	**Reason for Award**	**Award Name**	**Sponsor**	**Date**	**Award Type**
Fanglu Lu	Best paper award at CSW 2015	2015 CSW Best Student Paper Award	CSW 2015	Feb 2016	Scientific
Felix Fischer		Carl-Duisberg Prize	German Chemical Society	Mar 2016	Scientific
Seth Fortuna	Outstanding research in optical antenna nano-LED	Ross N. Tucker Award	Electronics Materials Symposium through UC Berkeley and Stanford University	May 2016	Scientific
Jianqiang Lin	Best student paper	Best student paper award	Compound Semiconductor	May 2016	Scientific

			Manufacturing Technology Conference		
Steven G. Louie	Scientific achievements	2017 Jubilee Professorship at Chalmers University of Technology	Chalmers University of Technology	June 2016	Scientific award
Ming C. Wu	For pioneering contributions in micro-opto-electro-mechanical systems	William Streifer Scientific Achievement Award	IEEE Photonics Society	June 2016	Scientific
Tsu-Jae King Liu	Elected to Intel Board of Directors	Board of Directors at Intel Corporation	Intel Corporation	Aug 2016	Industry
Seth Fortuna	Outstanding research in optical antenna nano-LED	Honorable mention best paper	International Semiconductor Laser Conference	Sept 2016	Scientific
Tsu-Jae King Liu	Teaching, advising, and mentoring students	SRC Aristotle Award	Semiconductor Research Corporation	Sept 2016	Education & Industry
Redwan Sajjad		SRC Techcon best in session award	SRC	Sept 2016	Scientific paper award
Xin Zhao	Best Paper	Best in Session Award	SRC Techcon 2016	Sept 2016	Scientific
Tsu-Jae King Liu	Academic Leadership	CITRIS Athena Award for Women in Technology	Center for Information Technology Research in the Interest of Society (CITRIS)	Oct 2016	Scientific
T M Swager	Chemical/Biological Sensing: Science and Real-World Applications	2016 Gustavus John Esselen Award for Chemistry in the Public Interest	Northeastern section of the Amer. Chem. Soc.	2016	Scientific
TM Swager	Outstanding achievement in chemistry	2017 Linus Pauling Medal	Northwestern sections of the American Chemical Society	2017	Scientific

3. Graduates

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Alexandra Fleitas	B.S.,EE, FIU	December 2016	4	N/A
Yee Ling Gan	B.S.,EECS, MIT	May 2016	4	Twitter
Terrell Glenn	B.S., Physics, Morehouse College	May 2016	4	Graduate Student at Purdue University
Surabhi Madhvapathy	B.S., MSE, UC Berkeley	May 2016	4	Graduate Student at Northwestern University
Mariana Martinez	B.S., EE, UTEP	December 2016	4	N/A
Hannah Masten	B.S.,EE, Auburn University	December 2015	4	Graduate Student at University of Michigan
Eric McShane	B.S., CE & Physics, Cornell University	May 2016	4	Graduate Student at UC Berkeley
Allison Perna	B.S., MSE, Carnegie Mellon University	May 2016	4	Graduate Student at Purdue University
Miles Rusch	B.S., Engineering, Physics, UC Berkeley	May 2016	4	Graduate Student at UC Berkeley
Ava Tan	B.S., Physics, Cornell University	May 2016	4	Graduate Student at UC Berkeley
Zeyan Xu	B.S., Physics, University of Texas at Dallas	December 2015	4	Glint Photonics

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree*	Placement
Ali Hadjikhani	Ph.D.	August 2016	3	University of Connecticut
Adamandios Manoussakis	M.S., ECE	December 2015	2	Sandia National Lab, NM
Mahmut Tosun	Ph.D., AS&T	May 2016	4	Apple
Tao Yu	Ph.D.	May 2016	5	ADI Inc.

Postdocs

Name	Departure Date	Placement (where did they go?)
Sergio Almeida	October 2016	Postdoc, UC Berkeley, E^3S, Theme 2
Ji Cao	March 2016	N/A
Kimihiko Kato	June 2016	University of Tokyo
Seunghyun Lee	February 2016	Professor at Kyung Hee Univ., Korea
Thomas Marangoni	May 2016	DOW Chemicals
Alexis Peschot	December 2015	CEA-Leti
Tania Roy	May 2016	Assistant Professor at University of Central Florida
Ellen Sletten	August 2015	Assistant Professor at UCLA
Sangwan Kim	February 2016	Postdoc, UC Berkeley
Annie Wang	June 2015	MIT Research Staff
Richard Wilson	June 2016	Assistant Professor at UC Riverside

4a. General Outputs of Knowledge Transfer Activities

Patents:

Patent Name	Inventors/Authors	Number	Application Date	Receipt Date
Alcohol-based digital etch for III-V nanostructures	Wenjie Lu, Xin Zhao and Jesus A. del Alamo	MIT case 19115	Nov 2016	
Decoupled Absorption/Gain Region Bipolar Phototransistor	Chris Keraly, Ryan Going, Eli Yablonovich, Ming Wu	BK-2015-111-1	Mar 2016	
Method for Passivation/Reparing Defects on Semiconductor Surfaces	M. Amani, D.-H. Lien, D. Kiriya, J. Bullock, A. Javey	Provisional Patent 62/242,427	Oct 2016	
Method and application of thin-film membrane transfer	V. Bulovic, W. Chang, J. H. Lang, A. Murarka and A. I. Wang	9,391,423 B2		July 2016
Electronically controlled squishable composite switch	T. L. Andrew, V. Bulovic, J. C. Grossman, J. H. Lang, A. Murarka, F. Niroui, S. Paydavosi, A. I.-J. Wang and F. Yaul	9,419,147 B2		Aug 2016

4b. *Other Outputs of Knowledge Transfer Activities*

a. Jeffrey Lang presented an invited seminar on MEMS/NEMS at Rutgers University in April 2016 where squitches was motivated via the E3S mission, and described.
b. Farnaz Niroui will present an invited seminar at BU on December 8, 2016, and will present work on squitches and plasmonics. (This has an added educational purpose, motivating the senior undergraduate and graduate students to pursue nanotechnology.)
c. Farnaz Niroui will give a seminar at the MIT Lincoln Laboratory in December. The lab is interested in our newly-developed fabrication techniques.

5a. *Participants*

In the current reporting period, the Center has 121 participants. Funding of faculty, postdoctoral, graduate student, and undergraduate student participants are summarized as follows.

Period 7	**Summer**	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	12	3	0	7	22

	Funded by E3S			**Other Funding Source**	**Total Participants**
Category	50% or more	Less than 50%	**Total**		
Postdocs	6	3	9	8	17
Grad Students	16	11	27	17	44
Undergrads	0	21	21	1	22
TOTAL					**83**

PARTICIPANTS - PERIOD 7

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Veteran		Citizenship	
23	Faculty	11	Berkeley	18	E.E.C.S	18	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	0	Yes	16	US Citizens
		8	MIT	1	Mats Sci	4	F	0	Visual Impairment	18	Not Hispanic or Latino	6	Asian	22	No	6	Permanent Resident
		1	Stanford	2	Chemistry			0	Mobility/Orthopedic Impairment	3	Decline to State	0	Black or African American			0	Other non-US Citizen
		1	UTEP	1	E.E.			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	LATTC					20	None			14	White			0	Not Available
		1	FIU					2	Decline to State			2	Decline to State				
		0	Other					0	Not Available			0	Not Available				
17	Postdocs	12	Berkeley	3	E.E.	9	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	0	Yes	4	US Citizens
		2	MIT	0	Mats Sci	8	F	0	Visual Impairment	14	Not Hispanic or Latino	9	Asian	17	No	0	Permanent Resident
		3	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	1	Black or African American			13	Other non-US Citizen
		0	UTEP	2	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	FIU	10	EECS			17	None			7	White			0	Not Available
				1	EECS/RLE			0	Decline to State			0	Decline to State				
								0	Not Available			0	Not Available				
44	Graduate Students	27	Berkeley	27	E.E.C.S	40	M	0	Hearing Impairment	2	Hispanic	1	American Indian or Alaskan Native	0	Yes	20	US Citizens
		12	MIT	3	MSE	3	F	0	Visual Impairment	33	Not Hispanic or Latino	21	Asian	44	No	3	Permanent Resident
		2	Stanford	0	Physics	1	N/A	0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American			19	Other non-US Citizen
		1	UTEP	4	E.E			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			1	Decline to State
		2	FIU	7	Chemistry			43	None			18	White			1	Not Available
				3	Other			1	Decline to State			3	Decline to State				
22	Undergraduate Students	1	Berkeley	8	E.E.	14	M	0	Hearing Impairment	3	Hispanic	0	American Indian or Alaskan Native	0	Yes	17	US Citizens
		1	MIT	5	EECS	8	F	0	Visual Impairment	19	Not Hispanic or Latino	4	Asian	22	No	4	Permanent Resident
		0	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American			1	Other non-US Citizen
		2	UTEP	3	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	LATTC	1	ChemE			22	None			11	White			0	Not Available
		0	CCC	3	Other			0	Decline to State			1	Hispanic				
		1	FIU					0	Not Available			3	Decline to State				
		17	Other									0	Not Available				
4	Visiting Scholar	0	Berkeley	0	E.E.	4	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	4	N/A	1	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	4	Not Hispanic or Latino	0	Asian	0	No	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	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	FIu	0	ChemE			4	None			3	N/A			3	Not Available
		4	Other	4	N/A			0	Decline to State			1	Decline to State				
11	Staff	10	Berkeley	0	E.E.	5	M	0	Hearing Impairment	0	Hispanic	1	American Indian or Alaskan Native	0	Yes	9	US Citizens
		0	MIT	0	Mats Sci	6	F	1	Visual Impairment	10	Not Hispanic or Latino	3	Asian	11	No	1	Permanent Resident
		1	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American			0	Other non-US Citizen
		0	UTEP	10	E3S			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander			0	Decline to State
		0	FIU	1	Other			9	None			3	White			1	Not Available
								0	Decline to State			0	Decline to State				
								1	Not Available			1	Not Available				
121	TOTAL PARTICIPANTS																

5b. Affiliates

AFFILIATES - PERIOD 7

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
8	Faculty	7	Berkeley	1	E.E.	4	M	0	Hearing Impairment	0	Hispanic or Lantino	0	American Indian or Alaskan Native	2	US Citizens
		0	MIT	0	Mats Sci	4	F	0	Visual Impairment	3	Not Hispanic or Latino	2	Asian	1	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Chemistry			0	Other	5	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	2	ME			4	None			1	White	5	Not Available
		1	CCC	3	Other			0	Decline to State			0	Decline to State		
		0	Other					4	Not Available			5	Not Available		
3	Research Scientists & Visiting Faculty	2	Berkeley	2	E.E.	3	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	2	Not Hispanic or Latino	1	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	1	Other non-US Citizen
		0	UTEP	0	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	1	Not Available			2	None			1	White	1	Not Available
		1	Other					0	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
14	Postdocs	11	Berkeley	12	E.E.	12	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		2	MIT	1	Mats Sci	2	F	0	Visual Impairment	13	Not Hispanic or Latino	8	Asian	1	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	12	Other non-US Citizen
		0	UTEP	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	0	ME			14	None			6	White	0	Not Available
				0	Other			0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
23	Graduate Students	16	Berkeley	13	E.E.	20	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	10	US Citizens
		2	MIT	1	Mats Sci	1	F	0	Visual Impairment	13	Not Hispanic or Latino	8	Asian	1	Permanent Resident
		0	Stanford	4	Physics	1	Decline	0	Mobility/Orthopedic Impairment	5	Decline to State	1	Black or African American	7	Other non-US Citizen
		0	UTEP	1	Chemistry	1	N/A	0	Other	3	Not Available	0	Native Hawaiian or Other Pacific Islander	2	Decline to State
		5	FIU	2	ME			18	None			5	White	3	Not Available
		0	Other	2	Other			2	Decline to State			6	Decline to State		
								3	Not Available			3	Not Available		
6	Undergraduate Students	4	Berkeley	4	E.E.	3	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	2	US Citizens
		0	MIT	1	Mats Sci	2	F	0	Visual Impairment	3	Not Hispanic or Latino	2	Asian	1	Permanent Resident
		0	Stanford	0	Physics	1	N/A	0	Mobility/Orthopedic Impairment	1	Decline to State	0	Black or African American	1	Other non-US Citizen
		0	UTEP	0	ChemE			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	1	Decline to State
		1	FIU	0	ME			5	None			2	White	1	Not Available
		0	LATTC	0	Other			0	Decline to State			1	Decline to State		
		1	Other	1	Not Available			1	Not Available			1	Not Available		

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
T	Pre-College Students	0	Berkeley	0	E.E.	x	M	0	Hearing Impairment	x	URM	0	American Indian or Alaskan Native	0	US Citizens
B		0	MIT	0	Mats Sci	x	F	0	Visual Impairment	x	Non-URM	0	Asian	0	Permanent Resident
D		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment			0	Black or African American	0	Other non-US Citizen
(x)		0	UTEP	0	Other			0	Other			0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	x	N/A			0	None			0	White	x	Not Available
		0	CCC					0	Decline to State			0	Decline to State		
		x	Other					x	Not Available			x	Not Available		
9	Staff	6	Berkeley	1	E3S	5	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	8	US Citizens
		3	MIT	1	MTL	4	F	0	Visual Impairment	7	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	2	OEOP			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	UTEP	4	TAP			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	1	Other			7	None			5	White	1	Not Available
								1	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
63 TOTAL AFFILIATES															

x = Data not available.

6. *Center Partners*

	Organization Name	Organization Type	Address	Contact Name	Type of Partner	160 hours or more?
1.	Applied Materials	Company	Santa Clara, CA	C.P. Chen	Knowledge Transfer	N
2.	Lam Research	Company	Fremont, CA	Nerissa Draeger	Research	Yes
3.	Samsung Electronics	Company	Seoul, Korea	Euichul Hwang	Research	Yes
4.	Axcelis Technologies	Company	Fremont, CA	Leonard Rubin	Research	N
5.	Western Digital Corporation	Company	Fremont, CA	Rabee Ikkawi	Research	N
6.	Tower Jazz	Company	Santa Clara, CA	Ed Preisler	Knowledge Transfer	N
7.	HPE Labs	Company	Palo Alto, CA	Mike Tan	Research	Yes
8.	Intel	Company	Hillsboro, OR, CA	Ian Young	Knowledge Transfer	N

9.	IBM	Company	Yorktown Heights, NY	Paul Soloman	Knowledge Transfer	N
10.	Applied Materials	Company	Santa Clara, CA	Lin Xue	Knowledge Transfer	N
11.	IMEC	Company	San Francisco, CA	Sam El Kazzi	Research	N
12.	Texas Instruments	Company	Santa Clara, CA	Ernest Ting-Ta Yen	Research	N
13.	IBM via Colleges of Nanoscale Science and Engineering (SUNY Polytechnic Institute)	Company	Yorktown Heights, NY	Sajjad Moazeni	Research	N
14.	TSMC	Company	Hsinchu, Taiwan	Pinyen Lin	Research	N
15.	CEA-LETI	French National Laboratory	Grenoble, France	Louis Hutin & Oliver Faynot	Education Knowledge Transfer	N
16.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Shawna Young	Education & Diversity	N
17.	MIT Office of the Dean of Graduate Education	University	Cambridge, MA	Eboney Hearn	Education & Diversity	N
18.	MIT Office of Digital Learning	University	Washington DC	Elizabeth COE	Education	N
19.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Merryl Owen	Education & Diversity	N
20.	UC Berkeley Summer Sessions	University	Berkeley, CA	Richard Russo	Education	N
21.	Berkeley Engineering Graduate Outreach	University	Berkeley, CA	Meltem Erol	Education & Diversity	N
22.	Berkeley Division of Equity and Inclusion	University	Berkeley, CA	Shaila Kotadia	Education & Diversity	N
23.	UC Berkeley Center for Teaching & Learning	University	Berkeley, CA	Richard Freishtat	Education	N
24.	Lawrence Hall of Science	Museum	Berkeley, CA	Lynn Tran	Education	N

25.	UC Berkeley School of Public Health	University	Berkeley, CA	Deborah Barnett	Education	N
26.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon	Education & Diversity	N
27.	UC Berkeley Science @ Cal	University	Berkeley, CA	Rachel Winheld	Education & Diversity	N
28.	Mathematics Engineering Science Achievement	Non-Profit	Oakland, CA	Julian Martinez	Education & Diversity	N
29.	Center for Integrated Quantum Material	University	Washington D.C.	Tina L. Brower-Thomas	Education & Diversity	N
30.	University of California Office of the President	University	Oakland, CA	Pamela Jenkins	Diversity	N
31.	Program YoUr Future	Non-Profit	Berkeley, CA	Alankrita Dayal	Education & Diversity	N
32.	UC Berkeley Black Graduate Engineering and Science Students	University	Berkeley, CA	Benjamin Osoba	Education & Diversity	N
33.	Center for Integrated Access Networks	University	Tucson, AZ	Amee Henning	Education & Diversity	N

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).	33
	The total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC) [Leveraged funding should include both cash and in-kind support related to Center activities, but not funds awarded to individual PIs.]	$728,566
4.	The number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF).	121

8. *Media Publicity of Center*

None.

IX. INDIRECT/OTHER IMPACTS

International Activities:

- **Donato Kava** and **Imani-Kai Horton**, both undergraduate researchers with the Center, spent 9 weeks at CEA-Leti, Grenoble France doing research in CMOS MIS Back Contact Structure Analysis and Electrical Characterization of Fuel Cells, respectively.
- **Steven Louie** was honored by the 2017 Jubilee Professorship at Chalmers University of Technology in Sweden.
- **Eli Yablonovitch** gave talks related to nanoelectronics, photonics, antennaLEDs at various locations outside the US: London, Uppsala (Sweden), Montreal, Peterhof (Russia). These seminars relate to Theme I and III research of the Center.
- **Felix Fischer** received the Carl-Duisberg Prize from the German Chemical Society and gave several talks on Theme I graphene nanoribbons work in Switzerland and Germany.
- **Jesus del Alamo** gave talks on Nanoscale III-V CMOS at various locations outside the US: Seoul, Leuven (Belgium), Madrid, Monterey (Mexico), Taiwan. Work presented was funded by E^3S as part of Theme I research.
- **H.-S. Philip Wong** gave an invited talk on next-generation computing (Theme IV related) at the University of Tokyo.

Education and Diversity:

Impacted >30% 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 will continue on until 2018. During the summer 2016 (Period 7), the Center hosted 11 community college students from science and engineering majors in 9 different labs on Berkeley's campus, including labs at Lawrence Berkeley National Laboratory (LBNL). These students research focused on robotics and biotechnology. Over the Center's lifespan, E^3S has hosted 71 community college students from 35 institutions from every region in the state of California. This total consists of projects advised by 34 faculty mentors and supervised by graduate student and postdoc mentors. Among this group, approximately 90% have transferred to a 4-year institution.

Community College Faculty: Similar to the expansion for the summer research program for community college students, the Center expanded its E^3S Teacher Fellows Program from two to six community college faculty with a NSF Research Experience for Teachers (RET) Site award. Beginning in Period 5, because of this new NSF award, was the implementation of curriculum development workshops on context-based learning, a pedagogical approach, which has been shown through assessments to enhance the students' interest in STEM. Closely aligned with project-based learning and inquiry-based science education, a context-based approach was selected to provide community college faculty a pedagogical method that can enhance learning, engage students, and improve the relevance of the science being taught. In Period 7, five community college faculty from electrical engineering/computer science, chemistry, materials science, and renewable energy departments at Bay Area community colleges conducted a nine-week research experience in the UC Berkeley labs of J. Wu, Yablonovitch, Javey, Kammen, and Fischer. In addition to coordinating the logistics (i.e., application, selection, placement, and implementation) for the summer RET program, the Center hosted four curriculum development workshops, three on context-based learning pedagogy and one on digital/online education with Berkeley's Center for Teaching and Learning, Berkeley Resource Center for Online Education, and School of Public Health; and Lawrence Hall of Science. At the conclusion of the summer, these faulty members each developed a course module or lab assignment, which will be taught at their respective community college during the 2016-2017 academic year.

HBCU Students: In Period 5, the Center was awarded supplemental funding from the University of California, Office of the President in order to create the UCB-HBCU REU programs. This award funds students to come to conduct summer research with UC Berkeley EE Faculty that are associated with a research center on campus (CIAN, E^3S, NASCENT, TANMS). The students are then able to go back to their HBCU and conduct research during the semesters at their home institutes. All 4 centers have committed to hosting the students for a second summer in their respective REU programs, so long as the student maintains eligibility. In Period 7, four students took part in this REU program. The Center hosted these students, and incorporated them into the E^3S REU workshops and activities.

Additional other impacts include:

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

X. REFERENCES CITED

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

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

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

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

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

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

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

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

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

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

[11] S. A. Fortuna, M. S. Eggleston, K. Messer, E. Yablonovitch, and M. C. Wu, "Large Spontaneous Emission Rate Enhancement from an Electrically-Injected nanoLED Coupled to an Optical Antenna," presented at the *IEEE Photonics Conference, Reston, VA,* 2015.

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

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

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

[15] J.T. Teherani, S. Agarwal, W. Chern, P.M. Solomon, E. Yablonovitch, and D.A. Antoniadis, "Auger Generation as an Intrinsic Limit to Tunneling Field-Effect Transistor Performance," *J. Appl. Phys*., vol. 120, pp. 084507 Aug 2016.

[16] I. R. Chen, C. Qian, E. Yablonovitch, and T.-J. K. Liu, "Nanomechanical Switch Designs to Overcome the Surface Adhesion Energy Limit," *IEEE Electron Device Letters,* vol. 36, pp. 963-965, 2015.

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

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

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

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

[21] J. Hong, B. Lambson, S. Dhuey, and J. Bokor, "Experimental test of Landauer's principle in single-bit operations on nanomagnetic memory bits," *Sci. Adv*., vol. 2, no. 3, pp. 1501492, Mar 2016.

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

[23] X. Zhao, J. Lin, C. Heidelberger, E. A. Fitzgerald and J. A. del Alamo, "Vertical Nanowire InGaAs MOSFETs Fabricated by a Top-down Approach," *IEEE International Electron Devices Meeting (IEDM)*, Washington DC, USA, December 9-11, 2013.

[24] J. Lin, D.A. Antoniadis, and J.A. del Alamo, "InGaAs Quantum-Well MOSFET Arrays for Nanometer-Scale Ohmic Contact Characterization," *IEEE Transactions on Electron Devices*, vol. 63, no. 3, pp. 1020-1026, Mar 2016.

[25] J. Lin, Y. Wu, J.A. del Alamo, and D.A. Antoniadis, "Analysis of Resistance and Mobility in InGaAs Quantum-Well MOSFETs from Ballistic to Diffusive Regimes," *IEEE Trans. Electron Devices*, vol. 63, no. 4, pp. 1464-1470, Apr 2016.E. J. Jolly, P. B. Campbell, and L. Perlman, *Engagement, Capacity and Continuity: A Trilogy for Student Success.* ed: GE Foundation, 2004.

[26] J. Lin, D.A. Antoniadis, and J.A. del Alamo, "Impact of Intrinsic Channel Scaling on InGaAs Quantum-Well MOSFETs," *IEEE Transactions on Electron Devices*, vol. 62, no. 11, pp. 3470-3476, Nov 2015.

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

[28] K. Kato, V. Stojanović, and T.-J. King Liu, "Non-Volatile Nano-Electro-Mechanical Memory for Energy-Efficient Data Searching," *IEEE Electron Device Letters*, vol. 37, no. 1, pp. 31-34, Jan 2016.

[29] B. Osoba, B. Saha, L. Dougherty, J. Edgington, C. Qian, F. Niroui, J.H. Lang, V. Bulovic, J. Wu, and T.-J. King Liu, “Sub-50 mV NEM Relay Operation Enabled by Self-Assembled Molecular Coating,*” IEEE International Electron Devices Meeting*, Dec 2016.

[30] K. He, C. Poole, K. F. Mak, and J. Shan, "Experimental Demonstration of Continuous Electronic Structure Tuning via Strain in Atomically Thin MoS2," *Nano letters*, vol. 13, no. 6, pp. 2931-2936, 2013.

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

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

[33] K. Han, F. I. Allen, and M. C. Wu, “Helium-Ion Milling of Gold Slot Antennas,” *CLEO*, May 2016.

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

[35] R.B. Wilson, J. Gorchon, C.-H. Lambert, Y. Yang, S. Salahuddin, and J. Bokor “Ultrafast magnetic switching of GdFeCo with electronic heat currents,” submitted to *Phy. Rev. B*.

[36] Y. Yang, R.B. Wilson, J. Gorchon, C.-H. Lambert, S. Salahuddin, and J. Bokor “Ultrafast Magnetization Reversal by Picosecond Electrical Pulses,” submitted to *Science*.

[37] R.B. Wilson, Y. Yang, J. Gorchon, C.-H. Lambert, S. Salahuddin, and J. Bokor, “Electric Current Induced Ultrafast Demagnetization,” submitted to *Physical Review X.*

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

[39] Y. Kang, J. Bokor, and V. Stojanovic, “Design Requirements for a Spintronic MTJ Logic Device for Pipelined Logic Applications,” *IEEE Trans. Electron Dev*., vol. 63, no. 4, pp. 1754-1761, Apr 2016.

[40] H. Ohno, T. Endoh, T. Hanyu, N. Kasai, and S. Ikeda, "Magnetic Tunnel Junction for Nonvolatile CMOS Logic," *IEEE International Electron Devices Meeting (IEDM 2010),* pp. 9.4.1-9.4.4, 2010.

[41] S. Emori, U. Bauer, S.-M. Ahn, E. Martinez, and G. S. D. Beach, "Current-Driven Dynamics of Chiral Ferromagnetic Domain Walls," *Nature Materials,* vol. 12, pp. 611-616, 2013.

XI. APPENDICES

Appendix A: Biographical Information of New Faculty and Staff

New Faculty in Period 7

Jing Kong is a Professor in the Electrical Engineering and Computer Science Department at MIT. The current research activity in her group involves CVD synthesis, characterization of graphene and related two dimensional materials, investigation of their electronic and optical properties and developing their applications. Professor Kong received her Ph.D. degree in Chemistry from Stanford University in 2002. Prior to joining the faculty at MIT in 2004, she was a research scientist at NASA Ames Research Center and a postdoctoral researcher at Delft University. She is member of the American Chemical Society, the American Physical Society, and the Materials Research Society. She received the 2001 Foresight Distinguished Student Award in Nanotechnology, the Stanford Annual Reviews Prize in Physical Chemistry (2002), and the MIT 3M Award (2005).

Steven G. Louie received his Ph.D. in physics from UC Berkeley in 1976. After having worked at the IBM Watson Research Center, Bell Laboratories, and University of Pennsylvania, he joined the UC Berkeley faculty in 1980. He is a member of the National Academy of Sciences (2005), fellow of the American Physical Society (1985), senior faculty scientist and Theory Facility Director of the Molecular Foundry at LBNL, and editor of the journal Solid State Communications. He has been awarded a Sloan Fellowship (1980), a Guggenheim Fellowship (1989), two Miller Professorships (1986, 1995), the U.S. Department of Energy Award for Sustained Outstanding Research in Solid State Physics (1993), the Lawrence Berkeley National Laboratory's Outstanding Performance Award (1995), the Aneesur Rahman Prize for Computational Physics of the American Physical Society (1996), the Davisson-Germer Prize in Surface Physics of the American Physical Society (1999), and shared with M. L. Cohen the Foresight Institute Richard P. Feynman Prize in Nanotechnology (2003). He is identified by the ISI as one of the most highly cited researchers in physics.

New Staff in Period 7

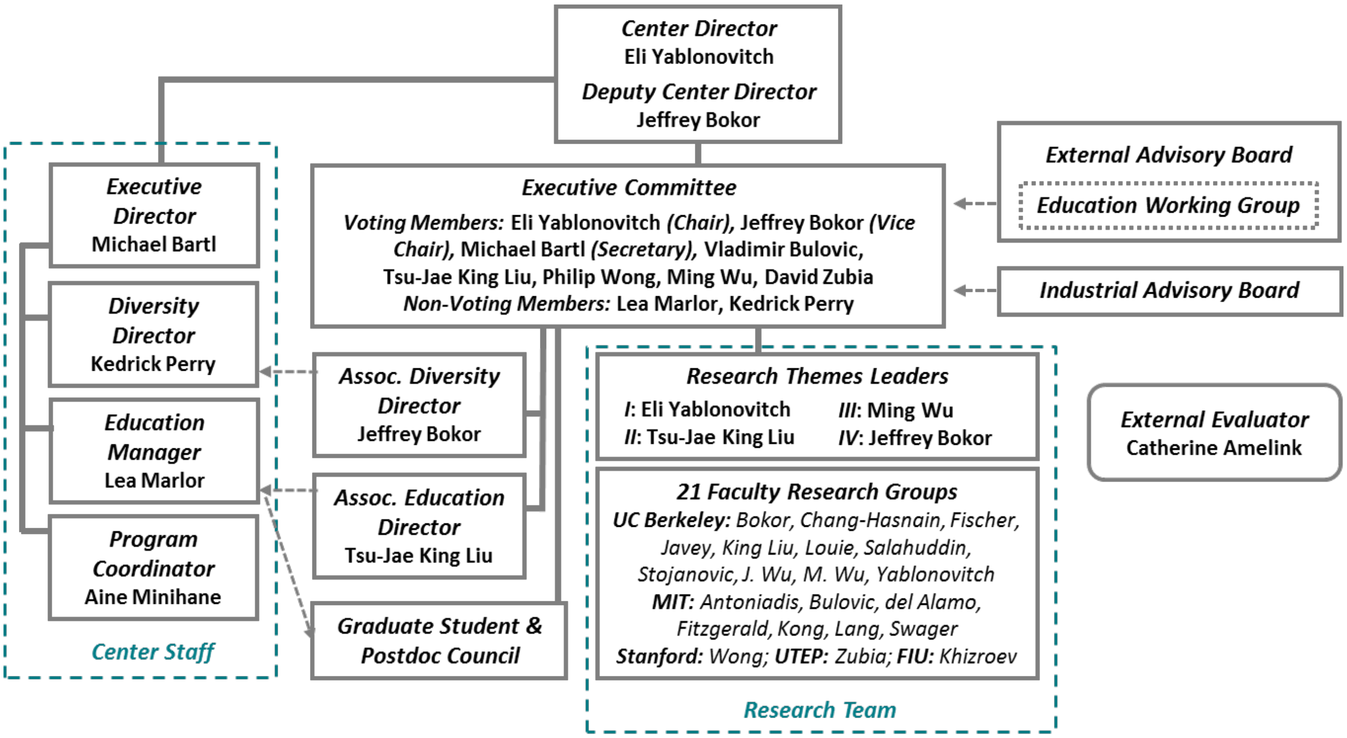
Dr. Kedrick B. Perry joined the Center for Energy Efficient Electronics Science (E3S) as Director of Diversity and Outreach in June 2016. Previously, he was Director of the Ronald E. McNair Scholars Program at Suffolk University in Boston where he prepared underrepresented, first-generation, and low income undergraduate students for graduate study. Prior to Suffolk University, he worked in the Office of Graduate Student Diversity Programs at the University of Virginia where he was committed to the recruitment, retention, mentoring, and graduation of a highly talented and diverse graduate student population. He received his doctorate in higher education from the University of Virginia where he studied logic modeling in graduate student affairs. Dr. Perry also has a Master of Public Administration and a graduate certificate in nonprofit management from North Carolina State University and a BA in English from the University of North Carolina at Chapel Hill.

Aine Minihane joined the Center for Energy Efficient Electronics Science (E3S) as Program Coordinator in November 2016. Previously, she served as Program Coordinator-Special Projects in Student Affairs at the University of California, Office of the President (UCOP). During her time at UCOP, she facilitated the planning, implementation, and tracking of specific events, programs, initiatives. In addition, she coordinated the development, planning, execution, and follow up of special projects, as directed, including Presidential Initiatives, communications and evaluation materials. Aine earned her B.A. in Native American Studies and a Minor in Political Science from the University of California, Davis.

Appendix B: Organizational Chart

Center for Energy Efficient Electronics Science (E^3S)

November 29, 2016



Appendix C: 2016 External Advisory Board Meeting Agenda

University of California, Berkeley
660 Sutardja Dai Hall
Tuesday, October 11,2016

Time	Duration (in minutes)	Topic	Speaker
8:00 AM	0:30	Breakfast & Check-In	
8:30 AM	0:10	Welcome, Review of Agenda	Eli Yablonovitch
8:40 AM	0:40	Center Overview: Energy Efficient Electronics	Eli Yablonovitch
9:20 AM	0:20	Center Management	Jeffrey Bokor
9:40 AM	0:10	Break	
9:50 AM	Theme I: Nanoelectronics		
	0:35	Research Presentations	Eli Yablonovitch, Matin Amani
	0:15	Q&A	
10:40 AM		Education & Diversity	
	0:40	Overview Presentations	Lea Marlor, Kedrick Perry
	0:20	Q&A	
11:40 AM	1:00	Lunch and Poster Session	
12:40 PM	Theme II: Nanomechanics		
	0:35	Research Presentations	Tsu-Jae King Liu, Benjamin Osoba
	0:15	Q&A	
1:30 PM	0:20	Knowledge Transfer	Michael Bartl
1:50 PM	0:10	Break	
2:00 PM	Theme III: Nanophotonics		
	0:35	Research Presentations	Ming Wu, Seth Fortuna
	0:15	Q&A	
2:50 PM	0:10	Break	
3:00 PM	Theme IV: Nanomagnetics		
	0:35	Research Presentations	Jeffrey Bokor, Jean Anne Incorvia
	0:15	Q&A	
3:50 PM			
	0:25	System Integration	Vladimir Stojanović
4:15 PM	0:20	Wrap-Up and Closing Remarks	Eli Yablonovitch
4:35 PM	0:10	Break	
4:45 PM	1:30	EAB Deliberations and Dinner	
6:15	0:30	Critical Feedback to E^3S	

Appendix D: 2016 Research Seminars Attendance

Dates	Faculty	Postdocs	Graduate Students	Undergrad Students	Staff	Other
2016 Seminar Series						
February 11	2	4	6	0	4	1
February 25	2	2	7	0	4	0
March 10	1	3	6	0	2	1
March 31	2	9	13	0	4	0
April 14	2	4	4	0	3	1
April 28	4	6	9	0	3	1
June 15	3	5	11	18	5	8
June 30	1	4	11	21	5	6
July 19	2	6	11	18	6	6
July 28	2	2	11	16	6	5
October 27	2	3	25	2	2	0
November 10	0	9	24	1	3	1
November 17	3	2	21	5	3	0

Appendix E: E^3S Professional Development Program

Objective: Equip E3S graduate students and postdocs with the skills and experiences needed to maximize their potential and success in their professional careers.

Requirements: Formal, but flexible.

- One outreach **OR** mentoring training area required
  - Diversity training embedded into outreach and mentoring
- Three other areas required

Training Areas

- Outreach
  - Attend outreach training (1 hour)
  - Take lead in 1 outreach event **OR** supporting role in 3 events
- Mentoring
  - Attend mentor training (1-hour)
    Mentor an undergraduate or high school student
- Leadership
  - Complete online or in-person leadership training (1 hour)
  - Take lead in 1 leadership event **OR** supporting role in 3 events
- Science Communication
  - Attend a science communication workshop (1 hour)
  - Present research to center (1 hour)
  - Present research to non-center audience (1 hour)
- Proposal Writing
  - Attend a proposal writing workshop (1 hour)
  - Submit a proposal
- Teaching
  - Complete online or in-person teacher training
  - Practice teaching **OR** develop course curriculum at any academic level of your choice
- Entrepreneurship
  - Attend a entrepreneurship workshop (1 hour)
  - Develop and submit a business plan **OR** complete innovation and commercialization course

Honors/Award: Receive E^3S professional development certificate for completion for required training areas.

Student Name:

____

Professional Development Interests & 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 8-9, 2013)
_____	BEARS Poster Session (UC Berkeley only): Present your research to industrial partners and potential donors (February 2013/2 hours)
_____	Graduate Student Visit Day – Poster Session: Present your research to admitted graduate students (March 2013/2 hours)
RESEARCH (Presentations)	
_____	Present at research seminar (fall or spring /1 hour)
_____	Present at journal club (summer /1 hour)
RESEARCH (Tours)	
_____	Cleanroom tour
_____	Lab tour
_____	Other, please specify: ________________________________
OUTREACH	
_____	Research presentation for non-scientists & engineers (e.g., teachers, middle and high school students (1 day/1-2 hours)
_____	Lead hands-on project for high school students (1 day/2 hours)
_____	Serve as judge at science fair (1 day/2-4 hours)
_____	Demonstrate research at science fair for middle and high school students (1 day/2-4 hours)
_____	Panel member: Talk about experience as scientist or engineer (1 day/1-2 hours)
_____	Present to summer research students on career development topics (e.g., creating posters, giving technical talks, applying for fellowships, writing scientific papers, applying to graduate school, etc.) (1 day/1-2 hours) Please specify topic(s) of interest: _________________________
OTHER *(must be approved by Education and Outreach Director)*	
_____	Please specify:
_____	Please specify:

Appendix F: E^3S REU Joint Recruitment Calendar

2016 Joint Recruitment Calendar

for Summer Research Experiences for Undergraduates and Engineering Graduate Diversity

July 2016			
UC Berkeley McNair conference	July 27-30	Berkeley, CA	E^3S
September 2016			
Tapia Diversity in Computing	September 13-16	Austin, Texas	COE
University of the District of Columbia	September 22	Washington D.C.	E^3S
Howard University	September 22	Washington D.C.	E^3S
Morgan State University	September 23	Baltimore, MD	E^3S
University of Maryland Baltimore County McNair Conference	September 23-24	Baltimore, MD	E^3S
October 2016			
Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Conference	October 13-15	Long Beach, CA	E^3S
Grace Hopper Conference	October 18-22	Houston, TX	COE
November 2016			
Society of Hispanic Professional Engineers (SHPE) annual conference	November 3-5	Baltimore, MD	E^3S
American Indian Science and Engineering Society (AISES) annual conference	November 10-12	Phoenix, AZ	E^3S

Appendix G: TTE REU Recruitment Calendar

October 2016		
Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Conference	October 13-15	Long Beach, CA
College of the Desert	October 12	Palm Desert, CA
LATTC	October 12	Los Angeles, CA
El Camino Community College	October 14	Torrance, CA
November 2016		
Society of Hispanic Professional Engineers (SHPE) Annual Conference	November 3-5	Baltimore, MD

Appendix H: UCB-HBCU Faculty Workshop

2016 UCB-HBCU Faculty Workshop

Agenda

Wednesday, March 16, 2016
Sutardja Dai Hall, Room 240, UC Berkeley

Time	*Duration*	*Topic*	*Speakers / Hosts*
8:10 AM	*0:10*	*Bus to Campus from LBL Guest House*	
8:20 AM	*0:25*	*Arrival and Breakfast*	
8:45 AM	*0:10*	Introductions, Review of Agenda & Meeting Goals	T.-J. King Liu
8:55 AM	*1:00*	Overview of UC Berkeley, College of Engineering and the EECS Department Review of the UCB-HBCU Program EE undergrad academic preparation at UC Berkeley (includes recent curriculum initiatives)	T.-J. King Liu
9:55 AM	*0:35*	Attendance at Freshmen Seminar	J. Bokor
10:30 AM	*0:10*	*Break*	
10:40 AM	*1:00*	Research Talks on Research Opportunities at UCB and Hampton U	A. Arias & V. Jagasivamani
	0:20	Research in the Arias Group	
	0:25	Introduction to Hampton U, EE Department, and research programs	
	0:15	Discussions – Faculty Collaboration & Support for Undergrad Intern	
11:40 AM	*1:20*	*Lunch with BGESS at the Faculty Club*	B. Osoba
1:00 PM	*1:00*	Research Talks on Research Opportunities at UCB and Morgan State U	A. Niknejad & M. Reece
	0:20	Research in the Niknejad Group	
	0.25	Introduction to Morgan State U and EE Department, including research programs	
	0:15	Discussions – Faculty Collaboration & Support for Undergrad Intern	
2:00 PM	*1:00*	Research Talks on Research Opportunities at UCB and Norfolk State U	M. Wu & P. Mead
	0:20	Research in the Wu Group	
	0:25	Introduction to Norfolk State U, EE Department, and research programs	

	0:15	Discussions – Faculty Collaboration & Support for Undergrad Intern	
3:00 PM	*0:15*	*Break*	
3:15 PM	*1:00*	Research Talks on Research Opportunities at UCB and Jackson State U	S. Desai *(representing A. Javey)* & M.A. Khan
	0:20	Research in the Javey Group	
	0:25	Introduction to Jackson State U, EE Department, and research programs	
	0:15	Discussions – Faculty Collaboration & Support for Undergrad Intern	
4:15 PM	*0:30*	Lab Tour: Arias Lab	N. Yamamoto
4:45 PM	*1:00*	*Break – rest & catch up on emails*	
5:45 PM	*1:45*	Pickup for Group Dinner at Downtown Berkeley (dinner at 6pm)	
7:30 PM		*End of Day 1*	

Thursday, March 17, 2016
Sutardja Dai Hall, Room 240, UC Berkeley

Time	*Duration*	*Topic*	*Speakers / Hosts*
8:00 AM	*0:10*	*Bus to Campus from LBL Guest House*	
8:10 AM	*0:20*	*Arrival and Breakfast*	
8 AM	*0:30*	Summer Internship Program: Expectations, Programming	L. Marlor
9:00 AM	*0:30*	Graduate Admission Process	T. Reardon
9:30 AM	*1:15*	Lab Tours: Marvel Nanolab & Chang-Hasnain Lab	J. Loo & I. Bhattacharya
10:45 AM	*0:15*	*Break*	
11:00 AM	*1:00*	Discussion with EECS Chair - includes feedback on 2015 program by HBCU faculty Working Lunch	T.-J. King Liu
12:00 PM		*Close of Workshop*	

Appendix I: 2016 E^3S Annual Retreat Poster Session

Day 1 – Thursday, September 15, 2016

University of California, Berkeley

MLK Building, Tilden Room (5th floor)

Time	Duration	Activity / Topic	Speakers
7:30 AM		*Breakfast & Check-In*	
8:00 AM		**Welcome, Review of Agenda**	**Eli Yablonovitch**
8:05 AM		**State-of-the-Center**	
	0:25	Ultra-Low Energy Devices: The Goals for 2020	**Eli Yablonovitch**
	0:10	Open Discussion	Discussion Leader: **Vladimir Bulović**
8:40 AM		**Theme I: Nanoelectronics**	
	0:15	Theme I Overview	**Eli Yablonovitch**
	0:10	Recent Progress in Nanowire Transistors	**Jesús del Alamo**
	0:20	Progress in Materials and Devices of 2D Semiconductors	**Ali Javey, Jing Kong**
	0:15	Graphene Nanoribbon Heterostructures: Electronic Structure and Novel Defect States	**Steven Louie**
	0:10	Progress in Graphene Nanoribbon Synthesis	**Felix Fischer**
	0:20	Open Discussion	Discussion Leader: **Eli Yablonovitch**
10:10 AM		*Break & Poster Setup*	
10:30 AM		**Theme II: Nanomechanics**	
	0:10	Theme II Overview	**Tsu-Jae King Liu**
	0:10	Squitch Design, Fabrication and Metrology	**Farnaz Niroui**
	0:15	Resistance Modulation in Strained TMDs for Low-Energy Switching – "Stritch"	**David Zubia, Sergio Almeida**
	0:20	Sub-50 mV NEM Relay Operation Enabled by Self-Assembled Molecular Coating	**Benjamin Osoba, Bivas Saha**
	0:20	Open Discussion	Discussion Leader: **Tsu-Jae King Liu**
11:45 AM		**Management and Center-wide Output**	**Michael Bartl**
Time	**Duration**	**Activity / Topic**	**Speakers**

12:00 PM		**Lunch and Poster Session**	
1:15 PM		**Theme III: Nanophotonics**	
	0:15	Theme III Overview	**Ming Wu**
	0:10	Transition Metal Dichalcogenide NanoLED	**Kevin Han**
	0:10	Enhanced Spontaneous Emission from an MoS_2 Monolayer using Cavity-Backed Slot Antennas	**Eli Yablonovitch**
	0:10	III-V Epitaxy for Antenna-Enhanced LEDs	**Chris Heidelberger**
	0:10	Compact Photoreceivers Based on InP Nanopillars Directly Grown on Silicon	**Indrasen Bhattacharya**
	0:20	Open Discussion	Discussion Leader: **Ming Wu**
2:30 PM		*Break*	
2:45 PM		**Theme IV: Nanomagnetics**	
	0:15	Theme IV Overview	**Jeffrey Bokor**
	0:10	Ultrafast Switching	**Yang Yang**
	0:10	Spin-Orbit Torque Switching	**Niklas Roschewsky**
	0:10	Nano Magnetic Tunnel Junction	**Ali Hadjikhani**
	0:10	CMOS Integration	**Jean-Anne Incorvia**
	0:20	Open Discussion	Discussion Leader: **Jeffrey Bokor**
4:00 PM		**System Integration**	
	0:20	System Integration Overview	**Vladimir Stojanović**
	0:10	Open Discussion	Discussion Leader: **Philip Wong**
4:30 PM		**E^3S Group Photo**	
5:00 PM		**Meeting with Industry Partners** *(Room: Madrone; 4th floor of MLK Building)*	
6:00 PM		**Dinner and Recognitions**	

7:15 PM	**End of Day 1**

Day 2 – Friday, September 16, 2016

University of California, Berkeley

MLK Building, Tilden Room (5th floor)

Time	Duration	Activity / Topic	Speaker / Facilitator
7:30 AM		*Breakfast*	
8:00 AM		**Diversity: Inclusivity and Workplace Environment**	
	0:50	Cultivating a Climate of Inclusive Excellence	**Kedrick Perry**
	0:25	Breakout Sessions	
	0:25	Open Discussion	Discussion Leader: **Jeffery Bokor**
9:40 AM		*Break*	
9:55 AM		**Building an Education Legacy: First Steps**	
	0:30	Education Overview	**Lea Marlor**
	0:15	Promoting Center Synergy	**Michael Bartl**
	0:15	e-Legacy Plans: E^3S Nanohub Website and e-Book	**Farnaz Niroui**
	0:25	Open Discussion	Discussion Leader: **Tsu-Jae King Liu**
11:20 AM		**Closing Remarks**	**Eli Yablonovitch**

Parallel Sessions	
Faculty Program *(Madrone; 4th floor of MLK Building)*	**Student & Postdoc Program** *(Tilden Room)*
Lunch & Legacy Dialog Session *(11:30 am – 1:00 pm)*	**Lunch & Etiquette Workshop** *(11:30 am – 1:00 pm)* & **Meeting with External Evaluator, Dr. Catherine Amelink** *(1:00 pm – 2:00 pm)* & **E^3S Lab Tours** *(2:00 pm – 3:30 pm)*
Adjourn Meeting (except for Executive Committee)	
Executive Committee Meeting *(1:00 pm – 2:15 pm)*	

2016 E^3S Annual Retreat Posters

	Title	Authors (*Poster Presenters)
Theme I		
1.	Modeling of Non-idealities to Predict Performance Limits of Tunnel Field Effect Transistors	**R. N. Sajjad***, W. Chern, U. Radhakrishna, and D. Antoniadis
2.	Centimeter-scale Growth of Monolayer MoS_2 Films	**P.-C. Shen***, X. Ji, Y. Lin, and J. Kong
3.	Intrinsic TFET On/Off Ratio due to Impact Ionization	**T. P. Xiao***, J. T. Teherani, S. Agarwal, W. Chern, P. M. Solomon, D. A. Antoniadis, and E. Yablonovitch
Theme II		
4.	Modeling of Band Gap Modulation in TMDs by NEMS	**S. Almeida***, A. Vidana, C. Qian, T.-J. King Liu, A. Javey, and D. Zubia
5.	Squitch Design, Fabrication and Metrology	**F. Niroui***, M. Saravanapavanantham T. Swager, J. Lang, V. Bulović
6.	Sub-50 mV NEM Relay Operation Enabled by Self Assembled Molecular Coating	**B. Saha***, B. Osoba, J. Edgington, L. Dougherty, C. Qian, F. Niroui, J. H. Lang, V. Bulović, T.-J. King Liu, and J. Wu
7.	Electrical and Optical Characterization of Strained TMDs via NEMS	**A. Vidaña***, P. Zhao, D.-H. Lien, S. Almeida, C. Qian, T.-J. King Liu, A. Javey, and D. Zubia
8.	Molecular Layers for Energy Efficient Nanoelectromechanical Switches	F. Niroui, **P. Wang***, M. Saravanapavanantham, W. J. Ong, E. Sletten, T. Swager, J. Lang, and V. Bulović
9.	Utilizing 65 nm CMOS BEOL Process for Vertical NEM Relays	**U. Sikder*** and T.-J. King Liu
Theme III		
10.	Compact Photoreceivers Based on InP Nanopillars Directly Grown on Silicon	**I. Bhattacharya***, S. Deshpande, W. Ko, F. Lu, and C. Chang-Hasnain
11.	TMDC Based nanoLEDs for High-Speed Energy-Efficient Optical Interconnects	**K. Han***, S. Fortuna, M. Amani, S. Desai, K. Messer, E. Yablonovitch, A. Javey, and M. C. Wu
12.	III-V and Group IV Materials and Integration for E^3S Optoelectronics	**C. Heidelberger*** and E. A. Fitzgerald
Theme IV		
13.	Modeling of Laser Induced Ultrafast Demagnetization and Switching of Ferromagnets and Ferrimagnets	D. Bhowmik* and S. Salahuddin
14.	Nonvolatile Hybrid CMOS-MRAM Circuits Using Three-Terminal Spin Orbit Torque MRAM for Normally-Off Computing	**J. A. C. Incorvia***, N. Roschewsky, C.-H. Lambert, Y. Kang, B. Eryilmaz, Z. Ju, V. Stojanović, S. Salahuddin, and H.-S. Philip Wong
15.	The Role of Electron Temperature in the Helicity-independent All-optical Switching of GdFeCo	J. Gorchon, R. B. Wilson, Y. Yang, **A. Pattabi***, J. Y. Chen, L. He, J. P. Wang, M. Li, and J. Bokor
16.	Spin-Orbit Torques in Ferrimagnetic GdFeCo Alloys	**N. Roschewsky***, T. Matsumura, S. Cheema, F. Hellman, T. Kato, S. Iwata, and S. Salahuddin
17.	Increasing "On/Off" Ratio in Sub-5-nm Magnetic Devices	B. Navarrete, **M. Stone***, A. Hadjikhani, K. Luongo, P. Wang, V. Safonov, J. Hong, J. Bokor, S. Khizroev
18.	Ultrafast Magnetization Reversal by Electrical Pulses	**Y. Yang***, R. B. Wilson, J. Gorchon, C. H. Lambert, S. Salahuddin, and J. Bokor
i-ETERN Undergraduate Poster		
19.	MIS Back Contact Structure Analysis	**D. Kava***

Appendix J: 2016 Student and Postdoc Survey

Year to Year Comparison

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

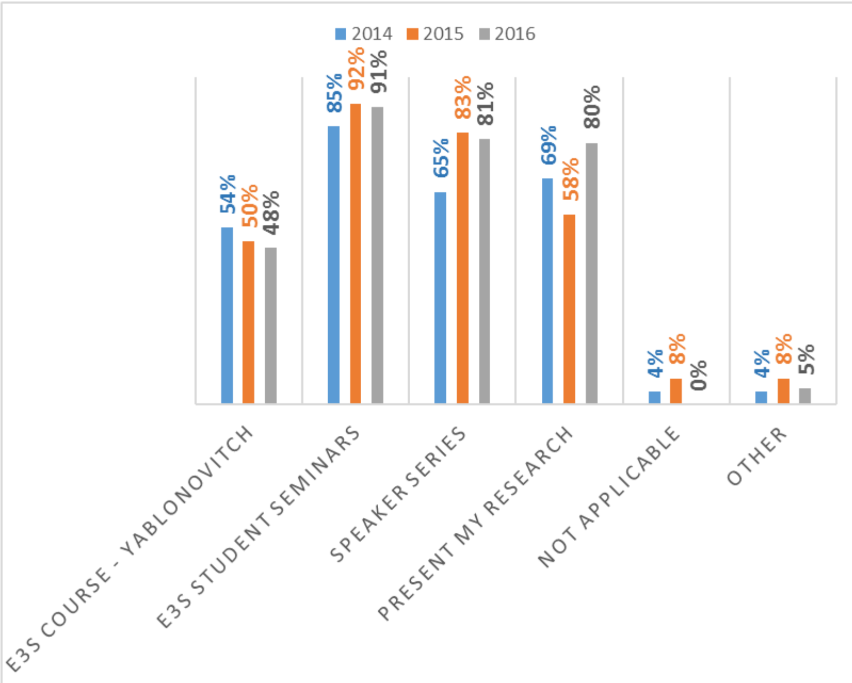
Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree

		2016	**2015**	**2014**	**2013**	**2012**
	Total Number of Respondents	22	29	26	21	20
	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.	4.3 ± 0.9	4.4 ± 0.6	4.6 ± 0.6	4.4 ± 0.5	4.2 ± 0.7
	The Center is making progress in its research program.	4.4 ± 0.9	4.4 ± 0.7	4.5 ± 0.6	4.1 ± 0.9	4.2 ± 0.5
	I understand how my project will contribute to the goals and vision of the Center.	4.8 ± 0.8	4.6 ± 0.5	4.5 ± 0.7	4.5 ± 0.6	4.3 ± 0.9
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.	4.3 ± 1.0	4.3 ± 0.9	4.6 ± 0.5	4.1 ± 0.8	4.1 ± 0.6
	The Leadership Team provides a research environment that is inclusive of different institutions, research themes, science and engineering disciplines, and individual differences.	4.5 ± 0.7	4.6 ± 0.6	4.7 ± 0.5	4.0 ± 0.9	4.1 ± 0.6
	The Leadership Team provides a research environment that crosses disciplinary and institutional boundaries.	4.2 ± 0.9	4.4 ± 0.8	4.5 ± 0.7		

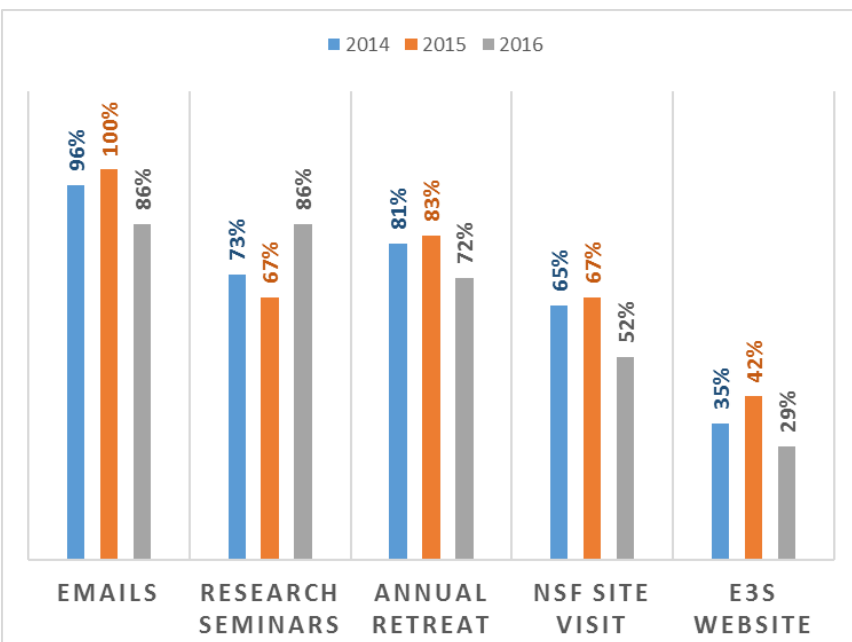
Communication	The Leadership Team keeps Center members well informed as there is a clear and timely communication on all Center activities.	4.4 ± 0.8	4.2 ± 0.8	4.7 ± 0.6	4.2 ± 0.6	4.2 ± 0.5
Collaboration	The Leadership Team provides a research environment that is collaborative.	4.3 ± 0.8	4.3 ± 0.8		4.2 ± 0.7	4.2 ± 0.7
	The Leadership Team is providing a work environment that values and encourages teamwork.	4.4 ± 0.8	4.4 ± 0.8	4.6 ± 0.5	3.9 ± 0.8	
	The Leadership Team is providing opportunities to collaborate.	4.3 ± 0.9	4.2 ± 1.0	4.8 ± 0.4	4.1 ± 0.9	
	The Leadership Team is providing tools that facilitate collaboration.	4.3 ± 0.9	4.3 ± 1.1	4.4 ± 0.8	4.1 ± 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.	3.5 ± 1.5	4 ± 1	4 ± 1	4 ± 1	3 ± 1
Decision Making	The Leadership Team is effective in making decisions on behalf of the Center.	4.5 ± 0.8	4.5 ± 0.6		4.2 ± 0.7	4.1 ± 0.6
	The Leadership Team is agile in making decisions on behalf of the Center.	4.4 ± 0.8	4.5 ± 0.6		4.1 ± 0.9	4.1 ± 0.7
	The Leadership Team is making decisions that are in the best interest of the Center.	4.3 ± 0.7	4.4 ± 0.6	4.5 ± 0.6		
Performance Focus	The Leadership Team promotes a culture permeating the Center's relationships, processes, and activities that recognize and values performance, and avoids possessiveness.	4.3 ± 0.9	4.3 ± 1.0	4.5 ± 0.6	4.1 ± 0.7	3.9 ± 0.9
	The Leadership Team is recognizing and evaluating me on my performance.	4.1 ± 1.0	4.0 ± 1.0	4.4 ± 0.7	3.8 ± 1.0	

Part B: Effectiveness of the Center's Activities

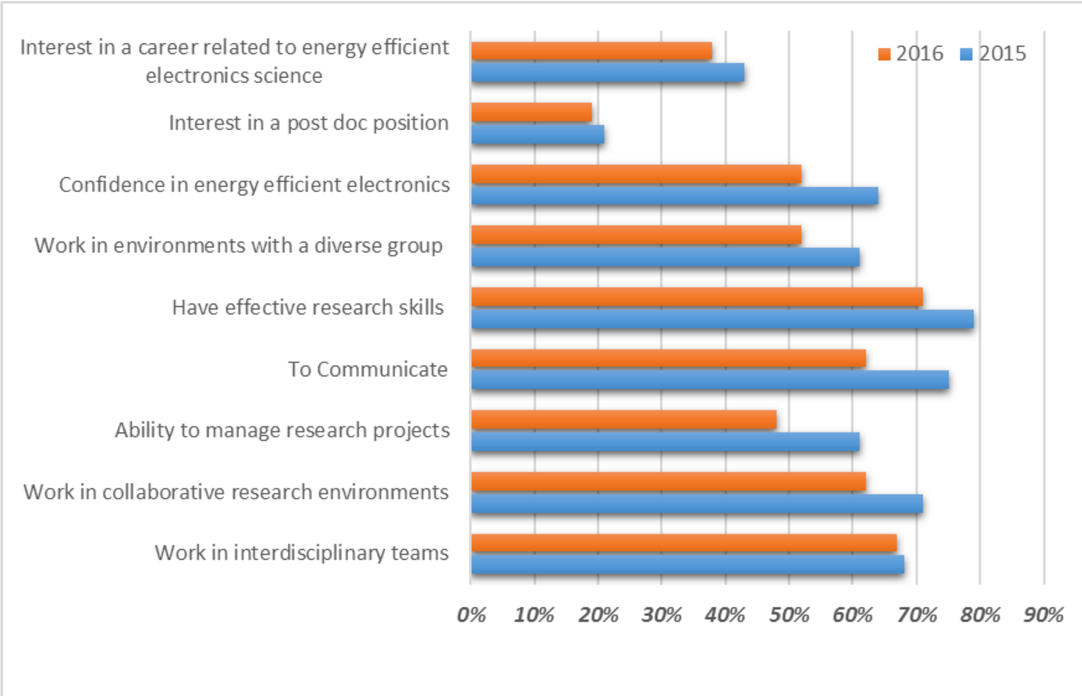
1. Respondents indicated the following activities are sharpening their understanding of low energy consumption device science and technology.



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

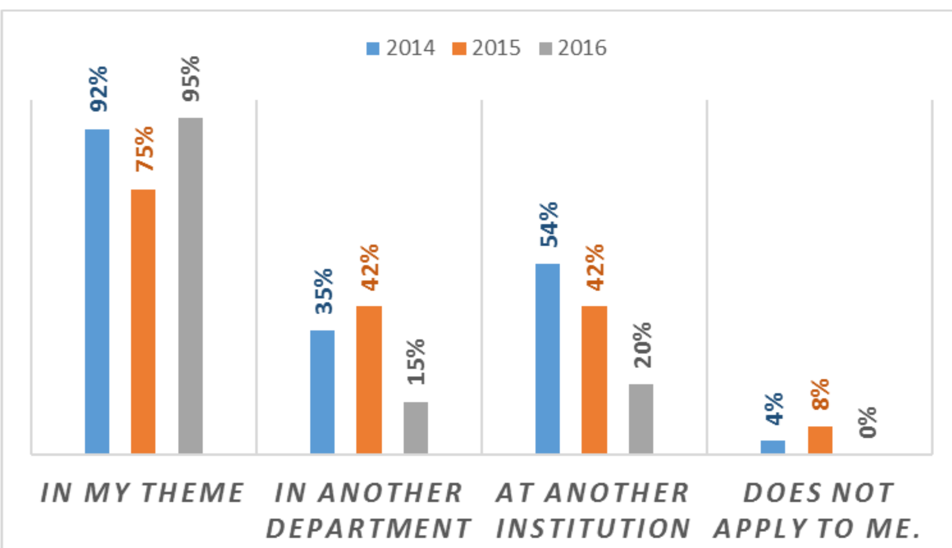


3. Respondents identified the following areas were positively impacted as a result of their experience at E^3S.

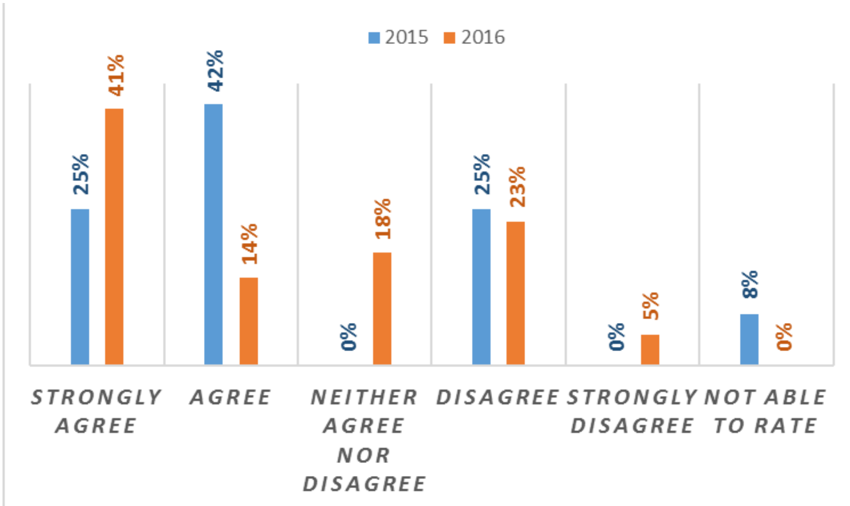


Part C: State of Collaborations

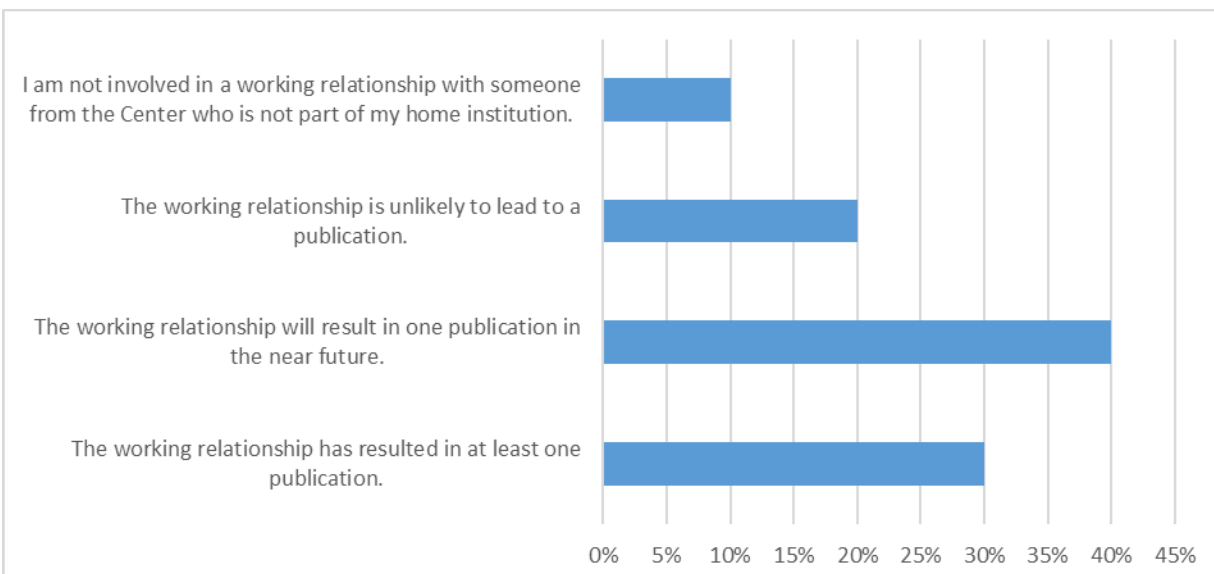
1. Respondents indicated that the following people helped with their E^3S research.



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 K: 2016 E^3S Faculty Survey

Year to Year Comparison

Leadership Survey

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

The E^3S leadership team is dedicated to:	**2014**	**2015**	**2016**
Creating an inclusive work environment.	5.0±0	4.9±0.2	4.9±0.2
Promoting a work environment that values and encourages teamwork.	5.0±0	4.9±0.3	4.9±0.2
Providing open and timely communication to me.	4.9±0.3	4.7±0.6	4.8±0.4
Recognizing and evaluating me on my performance.	4.7±0.7	4.7±0.6	4.3±0.8
Making decisions that are in the best interest of the Center.	4.8±0.4	4.8±0.4	4.8±0.4
Providing opportunities to collaborate.	4.9±0.3	4.9±0.3	4.8±0.4
Providing tools that facilitate collaboration.	4.7±0.6	4.6±0.6	4.7±0.5
Educating a diverse generation	4.9±0.5	4.9±0.3	4.9±0.3
Identifying fundamentally new concepts and scientific principles	4.9±0.2	4.9±0.2	4.8±0.4

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