Center for Energy Efficient
Electronics Science

Executive Summary

As part of the

Period 9 Annual Report (Draft)

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Berkeley UNIVERSITY OF CALIFORNIA
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STANFORD UNIVERSITY
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FLORIDA INTERNATIONAL UNIVERSITY
CALIFORNIA COMMUNITY COLLEGES CHANCELLOR'S OFFICE

Context Statement *(Executive Summary)*

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

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

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

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

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

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

The three most important requirements for the logic switch are:

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

The requirements for ultralow energy optical communication are:

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

Strategic Research Plan & Rationale

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

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

Theme I: Nanoelectronics

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

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

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

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

Theme II: Nanomechanics

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

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

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

Theme III: Nanophotonics

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

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

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

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

Theme IV: Nanomagnetics

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

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

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

Education & Diversity Strategic Plan

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

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

Graduate Education

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

Undergraduate Education

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

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

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

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

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

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

Online Education

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

Knowledge Transfer

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

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

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

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

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

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

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

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

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

	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center	P6: 40% P7: 45% P8-P10: 50%	(new for P6-10)				17 (55%)	23 (54%)	27 (50%)	30 (55%)
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate	P6: 85% P7: 85% P8-P10: 85%	(new for P6-10)				16 (70%)	22 (81%)	24 (80%)	30 (88%)
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering	P6: 80% P7: 80% P8-P10: 80%	(new for P6-10)				73 (55%)	102 (63%)	14 (33%)	TBD
Knowledge Transfer	Center publications	P2-5: 18 P6-7: 25 P8-P10: 30	21	21	27	46	39	37	31	47 (11 subm)
	Talks at peer-reviewed conferences	P6: 12 P7: 12 P8-P10: 15	(new for P6-10)				14	12	26	21
	Center sponsored symposia & workshops	P2: Baseline P3: 0 P4: 1 P5: 0 P6: 2 P7-9: 1 P10: 2	1	0	1	0	1	1	2	2
	External citations of publications *(cum)*	P3: 10 P4-5: 100 P6-10: 25% increase	15	178	393	719	1724 140% increase	2718 58% increase	4361 60% increase	6076 40% increase
	Industry contacts:									
	• Talks & Meetings	P2-10: 36	66	20	42	62	35	42	31	38
	• Industry Presentations	P2-10: 2	4	2	6	3	5	2	2	2

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

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

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

Research Accomplishments in Period 9

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

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

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

Theme I: Nanoelectronics – Key Accomplishments

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

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

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

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

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

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

Theme II: Nanomechanics – Key Accomplishments

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

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

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

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

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

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

Theme III: Nanophotonics – Key Accomplishments

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

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

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

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

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

Theme IV: Nanomagnetics – Key Accomplishments

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

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

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

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

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

System Integration – Key Accomplishments

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

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

Education and Diversity Accomplishments in Period 9

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

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

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

Knowledge Transfer Accomplishments in Period 9

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

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

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

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

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

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

Center Management Changes in Period 9

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

Table 1.2. *Center Output in Period 9*

Publications	
Peer Reviewed Journal Publications	26
Submitted for Review	11
Peer Reviewed Conference Proceedings	21
Books and Books Chapters	3
Conference Presentations	44
Other Dissemination Activities	21
Awards and Honors	13
Ph.D. and M.S. Graduates	7
Postdoc Alumni	6
Patents and Patent Disclosures	2

Summary of Plans for Period 10

Research Plans for Period 10

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Education and Diversity Plans for Period 10

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

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

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

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

Knowledge Transfer Plans for Period 10

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

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

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

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