National Science Foundation

SITE VISIT REPORT – Period Eight
Science and Technology Centers: Integrative Partnerships Program

Science and Technology Center (STC) for the
Energy Efficient Electronics Science (E^3S)
Lead Institution: UC Berkeley
Principal Investigator: Prof. Eli Yablonovitch

January 8-10, 2018

Executive Summary

The Energy Efficient Electronics Science (E^3S) Science and Technology Center (STC) is now in its eighth year of operation. Many issues raised in previous years have been resolved, and the Center is functioning in an efficient and highly productive level. The E^3S Center participants include eleven faculty members from UC Berkeley, six faculty members from MIT, and one faculty member each from Stanford, the University of Texas at El Paso, and Florida International University. The California Community College Chancellor's Office also participates as an Education partner. Industry partners are Applied Materials, HP Enterprise, IBM, Intel, and Lam Research.

The overall goal of the E^3S STC is to investigate and explore the fundamental science that governs the limits of energy-efficient operation of electronic, photonic, magnetic and nano-mechanical devices, including tunneling transistors, nanomechanical switches, optical on-chip communication and magnetic domain devices. An associated goal is to prepare the next generation of researchers and workforce, and a significant effort to develop education strategies and outreach programs has been established and is functioning at a high level. The range of device types that are under investigation provide options that could prove fundamental to establishing next generation communications, computing, sensing, display, and other technologies. However, the primary and main objective of the E^3S STC is to address the power consumption and dissipation issues in highly-scaled electronics that affect the energy efficiency of devices. The E^3S Center continues to address the important topic of high efficiency, low power electronics by investigating fundamental issues and properties of electronic materials and devices. The research team is focused on developing scientific knowledge for new generations of electronic devices that can operate at orders of magnitude lower switching energy than current generations of devices.

The various device technologies and approaches are organized into five separate themes, each with a theme leader supported by an appropriate number of students (both undergraduate and graduate), post-doctoral research associates, and staff. The five themes range in sophistication and maturity from long-term exploratory research (e.g., theme 1 focused upon tunnel transistors), to nanomechanical switches (e.g., theme 2 focused zero leakage switching) and magnetic devices (e.g., theme 4 focused upon nanomagnetic devices). All five themes represent long-term basic

research, as opposed to applied research with near-term goals. However, the nanomechanics and nanomagnetics research themes, in particular, each include new and exploratory devices that could easily result in near-term applications. Overall, the E^3S research topics are very well selected, and the research is very well directed and managed. A significant body of publications and patents have resulted.

The E^3S Team has strong technical and scientific competence and well-equipped laboratories necessary to make progress towards well defined research goals. The E^3S STC has initiated and developed a number of strong partnerships and educational programs with an impact on community colleges, as well as on undergraduate and graduate students. The Center has a solid pre-college and undergraduate outreach and engagement program. In particular, outreach programs have been implemented on campus-wide efforts at UC Berkeley and MIT for high school underrepresented minorities. In addition, the E^3S team has developed a strong program to engage community college students, expose them to state-of-the-art research, and transition them to further education opportunities. The E^3S Center organizes a biennial conference, the Berkeley Symposium on Energy Efficient Electronics, which has grown and now attracts over 100 participants. State-of-the-art topics in low-energy electronics are presented and discussed.

The E^3S Center is guided by the expertise of an External Advisory Board (EAB), which is composed of academic and industrial leaders in the field from university, industry, and national laboratories. The EAB Charter states: "The primary mission of the EAB is to offer an independent assessment of E^3S goals, plans, and accomplishments for research, education, diversity, knowledge transfer and center management." The synergistic interaction between the EAB and E^3S management facilitates and enhances the center's ability to achieve significant progress and advances.

RECOMMENDATIONS:
The Site Visit Team (SVT) recommends that the E^3S Center be funded for period nine.

Organization and Management

The E^3S Center is led by a very qualified and experienced management team led by Center Director, Prof. Eli Yablonovitch and Deputy Director, Prof. Jeffrey Bokor. The Center management is assisted and augmented by the Executive Director, Dr. Michael Bartl, who oversees the Center administration, all programmatic aspects, the Center budget, the operation of the Center, and the management of the Center's students and staff. The E^3S research areas are organized into five theme areas, each led by a faculty Theme Leader. The Center has established an Executive Committee that is led by the Director, Deputy Director and the Theme Leaders of each theme. The Associate Director for Education, Ms. Lea Marlor, and the Director of Diversity, Dr. Kedrick Perry, participate on the committee. The Site Visit Team (SVT) was impressed by the manner in which the decisions are made regarding the directions of the work and the education and outreach plans and programs. In addition to the Executive Committee meetings, there appears to be a robust discussion of the progress amongst the participants. The fact that the leaders appear to enjoy working together surely has a positive impact on the success of the Center. The surveys from the students and the postdocs affirm their satisfaction in working in the Center. The Executive Committee is advised by an External Advisory Board (EAB) and an Industrial Advisory Board (IAB). During this performance period, an education working group was created as a part of the EAB. The upper administrations of the participating institutions appear to be very supportive and engaged in the activities of the Center.

During the site visit review, the UC Berkeley Vice-Chancellor for Research, Prof. Randy Katz, gave very supportive statements to the SVT relative to institution plans and support for the E^3S Center. This discussion was seconded and augmented with statements from the upper administrations of the partner institutions, including Prof. Anette Hosoi, Associate Dean of the School of Engineering at MIT, Prof. Stacey Bent, Senior Associate Dean for Faculty and Academic Affairs at Stanford, Prof. Theresa Maldonado, Dean of the College of Engineering at the University of Texas at El Paso, Prof. John Volakis, Dean of the College of Engineering and Computing at Florida International University, and Associate Dean for Research at Florida International University, Osama A. Mohammad.

The SVT believes the Center Management is excellent and is very effectively leading the research, both in terms of subject and performance. Numerous state-of-the-art results have been demonstrated.

The SVT supports the participation of the Associate Director for Education, Lea Marlor, and the Director of Diversity, Kedrick Perry, on the Executive Committee. Also, Executive Director Michael Bartl adds strength and enhancement to the area of knowledge transfer. The E^3S Center is organized with an excellent balance of technical and administrative leadership.

Intellectual Merit: Proposed Research and Accomplishments to Date

Progress, concerns, and recommendations of the five themes are described below.

Theme I: Nanoelectronics

During Period 8, the team continues the long-term fundamental focus on material quality and defects, parallel approach between top-down and bottom-up preparation of materials, as well as vertical and lateral tunneling, and in-depth understanding of spectroscopic sharpness. As the result, vertical nanowire InGaAs/InAs tunneling FET was fabricated with record small diameters on the order of 10 nm, to study the underlying physics of tunneling in semiconductors, while revealing the issue of defect assisted tunneling in the OFF-state. Sub-thermal subthreshold behavior over two orders of magnitude of current at room temperature were demonstrated; however, at low current density, indicative of the tunnel distance modulation mechanism. Edge defect sites of 2D transition-metal dichalcogenides were successfully passivated by using the superacid method developed during Period 7 in combination with scanning probe lithography technique for edge patterning. Bottom-up synthesis for heterostructure graphene nanoribbons continued to be developed, with particular emphasis on the introduction of orbitally matched trigonal planar heteroatom dopants such as N, O, and S. Scanning tunneling spectroscopy studies of these samples revealed a narrowing of the band gap by 0.2-0.3 eV per dopant atom per monomer unit. Finally, it was shown that the Lorentzian line shape was only an approximation, and auto-correlation functions could correctly describe the line shape, i.e. it is exponential at long times, but parabolic at short times.

CONCERNS:

- The plan for concluding this theme by the end of Period 10 should be more specific.

- The stability of superacid surface treatment needs to be better established.
- There appears to be going back and forth between 2D and III-V materials, inconsistent with the new emphasis on energy-filtering tunneling as opposed to distance tunneling.

RECOMMENDATIONS:

- Model an ideal tunneling FET made of appropriate conducting, semiconducting and insulating 2D layers, density of states, tunneling distance, etc., without any band tail state. Show that such a tunneling FET has not only 10^6 current on/off ratio, but also adequate transconductance of 1 mS/micron.
- Demonstrate an inversion-mode 2D MOSFET before the end of Period 10. Use such a device to evaluate the interface state and other figure of merits for benchmarking against state-of-the-art Si MOSFETs.

Theme II: Nanophotonics

The goal of E^3S nanophotonics researchers is to dramatically improve the interconnect energy efficiency from currently used ~20,000 photons per bit to just a few hundreds of photons per bit or less. The team's approach of using optical antenna to enhance the spontaneous emission as well as the modulation speed of nano-quantum well LED is very intriguing. The team has achieved an impressive 200-fold enhancement of spontaneous emission with an overall efficiency of 44% under current injection. Excellent progress has been made in terms of reducing the surface recombination velocity. It was shown that it is possible to increase the LED efficiency and modulation speed simultaneously via doping engineering. It was good to see that the team is also investigating other approaches including a hybrid of metal-dielectric antenna to minimize the metallic loss. The team has also attained a good fundamental understanding of the basic requirements of nano-photoreceiver and design trade-off to reach 100 aJ/bit performance. Team members have demonstrated selective growth of quantum-well in nanopillar lasers directly on silicon emitting within the silicon-transparent wavelength as well as stimulated and spontaneous emissions from the nanopillars directly coupled to silicon waveguides under optical excitation. Detector/pre-amp circuit innovation has received interest from the silicon photonics industry.

CONCERNS:

- The progress on the nano-photoreceiver was not clear.

RECOMMENDATIONS:

- While a 200-fold in emission has been obtained, it appears that the emission efficiency is still low. Further enhancement is expected if the overlap between antenna coupler efficiency peak wavelength and LED emission peak wavelength can be further improved. The SVT recommends that the Center conducts further fine tuning in device design and processing.
- The SVT recommends that the Center to pin down the choices for material and device architecture of nano-photoreceiver, and to demonstrate the integration of antenna-nanoLED with nano-photoreceiver on InP platform in a year.
- The SVT recommends that the Center conducts background works for integrating nano-LED and nano-photoreceiver with silicon photonic waveguide during the supporting period.

- Continue to engage with silicon photonics industry and to identify niche applications.

Theme III: Nanomechanics

Nanomechanical switches are attractive because of their potential zero-power off state. Part of the E^3S efforts builds on the earlier DARPA N/MEMS S&T program, however lower voltage / power was not a main emphasis in the DARPA program. Several nanomechanical switches are under development, including 3 and 4 terminal switches, as well as switches based on squeezing or stretching thin films ("squitch" and "stritch"). The main challenges are hysteresis in transition (setting a limit on the minimum switching voltage) and adhesion / wear issues with nanomechanical contacts.

The team has demonstrated squitch with voltage less than 100 mV. Device development is occurring in collaborations across the different E^3S sites, involving key contributions in particular from FIU and UTEP. The current size mismatch between nanomechanical switches and CMOS is being reduced by new designs with vertical switches that utilize the metal interconnect layers in CMOS chips. Integration with CMOS has progressed, with a tape-out at TSMC currently pending (see Section 3.e).

CONCERNS:

- The team has experienced difficult post-processing on CMOS, with a goal to achieve single nanometer gaps between metal lines.
- Reliability and life-time of switches remain potential challenges for nanomechanics.
- It is not clear whether the squitch and the CMOS back end-of-line (BEOL) approaches can be combined before Year 10 ends.

RECOMMENDATIONS:

The team should plan experiments to gather additional data on the reliability of molecular coatings in nanomechanical switches.

Theme IV: Nanomagnetics

The major goal of this research theme is development of an ultrafast, energy-efficient nanomagnetic switch, which can be used for non-volatile memory and logic applications. The ultimate performance metrics targeted by this Theme are sub-10 ps switching time and aJ-scale switching energy. Particularly, the Theme pursues current-induced switching of metallic nanomagnets, which can be achieved at low voltage levels making this technology compatible with low-voltage devices being developed in other Themes of the Center.

In this review period, researchers of this Theme made several important advances building upon two major breakthroughs reported in the previous review period. The first discovery reported last year was ultrafast switching of GdFeCo magnetization by a sub-10 ps electric current pulse, which was the first example of an ultrafast magnetic memory prototype. The other discovery reported last year was the demonstration of spin orbit torque switching of thick GdFeCo layers with bulk perpendicular anisotropy, which provided a pathway towards scaling down of spin orbit torque memory via boosting its thermal stability.

This year, several major strides towards development of a practical ultrafast nanomagnetic switch were made. First, the Theme PIs discovered that GdCo ferrimagnet is more suitable for building scalable ultrafast memory than GdFeCo. The GdCo nanomagnets were shown to retain strong perpendicular magnetic anisotropy when scaled down to at least 50 nm dimensions. Second, the PIs demonstrated ultrafast switching of GdCo nanodots as small as 200 nm in diameter, and electrical detection of magnetization in 50 nm GdCo nanodots. These are important steps towards development of a scalable ultrafast magnetic memory. Third, the PIs demonstrated ultrafast switching of a ferromagnet (CoPt) via exchange coupling to a GdFeCo ferromagnetic layer. This is a very significant step towards the development of a reliable readout for the ultrafast memory because high tunneling magneto-resistance can be achieved with ferromagnetic elements but is unlikely to be realized with ferrimagnets. Fourth, the PIs made progress towards integration of GdCo nanodot elements with ultrafast CMOS circuitry for demonstration of on-chip ultrafast magnetic memory. Such a demonstration is likely to stimulate the transfer of this technology into research and development labs of major semiconductor companies.

In addition, two new important discoveries were made in this review period. First, a new type of spin orbit torque with out-of-plane spin current polarization arising from a symmetry-breaking crystalline conductor was discovered. This discovery is very promising for zero-field spin-orbit torque switching of perpendicular nanomagnets used in magnetic memories. Second, preliminary data on energy-efficient current-induced switching of magnetization in ultra-small magnetic tunnel junctions with ferromagnetic nanoparticles embedded in the tunnel barrier were presented in a poster. This line of research is very promising for the development of the next generation of ultra-dense spin torque memory.

The SVT is impressed with the steady progress demonstrated by the Nanomagnetics Theme towards realization of a practical ultrafast magnetic switch. It is good to see that the initial scientific discoveries of the Theme are followed up by a strong push towards development and demonstration of a new viable technology based on these discoveries. The SVT agrees with the next year plan of the Theme to focus on component integration for realization of CMOS-integrated nonvolatile memory and latch devices. The SVT is also impressed by the productive collaborations within the Theme.

RECOMMENDATIONS:

- Zero-field switching of perpendicular magnetization by the newly-discovered spin torque with out-of-plane spin polarization should be pursued in the next reporting period.
- Integration of magnetic materials exhibiting ultrafast switching (e.g., GdCo) into magnetic tunnel junctions (MTJs) with high tunneling magnetoresistance appears to be the last major roadblock for demonstration of a fully integrated ultrafast magnetic memory. The SVT recommends to work on GdCo-based MTJ multilayer stacks that can exhibit high tunneling magnetoresistance. A possible pathway is development of MTJ multilayers with a GdCo/ferromagnet composite free layer having (100) crystallographic texture at the ferromagnet/MgO interface, which is necessary for achieving high tunneling magnetoresistance.
- The progress towards realization of ultra-small magnetic tunnel junction elements with embedded magnetic nanoparticles is very promising. The SVT recommends to

characterize tunneling magneto resistance (TMR) and the critical current in such devices as a function of the device lateral dimensions. The ultra-small devices also give excellent opportunities for understanding of the impact of the sample fabrication processes (such as edge damage and contamination) on TMR and the critical current.

Theme V: Integration

In the past year, the E^3S Center has focused their technology development towards the current massive wave of neural network and machine learning activities that span applications from computer vision, self-driving cars, IoT, etc. Modeling and simulations have shown that substantial improvements in average power consumption may be possible for neural network processors ("intelligent processing units - IPUs") with integrated non-volatile memory due to low-power off-states. Current mechanical switch designs provide an advantage for off-cycles in the millisecond range. It is anticipated that the next generation will further reduce this number by 2-3 orders of magnitude, making this approach attractive for many practical sensing scenarios. E^3S has demonstrated a clear path for nanomechanics and nanomagnetics integration. Nanomechanics switches are being integrated at the wafer-scale in commercial foundry processes, e.g. with TSMC. A tape-out of switch designs implemented in the metal interconnect layer of CMOS memory is pending and is expected to be completed in the coming months. Nanomagnetics has been integrated on top of CMOS in collaboration with Applied Materials. There also exist collaborations with SUNY Albany for magnetic switches on 300 mm wafers. In nanophotonics, there is an ongoing effort for integration of antenna LEDs on InP, and on more efficient interconnects where currently most of the power losses occur.

CONCERNS:

- The system integration of nanoelectronics devices seems to be in the more distant future.

RECOMMENDATIONS:

- The team should seek to demonstrate applications with integrated nanomechanics and nanomagnetics systems.

Broader Impact: Education Plan and Accomplishments to Date

The educational activities of the Center are a strength. There are focus areas on high school seniors, undergraduate students, and the graduate students and postdocs of the Center. The activities are well integrated with diversity and inclusion efforts – also a strength of the Center.

High school students are primarily reached through the MIT Online Science, Technology and Engineering Community (MOSTEC). This year, 100% of MOSTEC students were from underrepresented groups. This is primarily an online program, though there is an in-person, end-of-program conference/workshop hosted at the MIT campus.

For undergraduate students, there are several REU programs that expose students to the Center's research. The programs that surround these research experiences are important, and the Center

uses the Model of Student Success (developed by Jolly, et al) to inform their activities. These activities fall into three areas characterized by engagement, capacity building, and continuity. The engagement activities are designed to build community among the participants and between the participants and Center personnel. Capacity building activities include trainings and workshops that teach students the skills that they need to be successful in their research program. Continuity activities are those that set students up for future success beyond their current stage. The SVT commends the intentionality around these activities.

The NSF-sponsored TTE REU (Transfer to Excellence – Research Experiences for Undergraduates) Program is a demonstrated success, as evidenced by the significantly higher successful transfer rates of community college students into 4-year institutions as compared to both the California and national averages.

The NSF-sponsored RET (Research Experiences for Teachers) program for community college faculty provides additional interactions with community colleges. However, Center personnel cite continued challenges in attracting community college faculty to the program, due to other lucrative opportunities available to community college faculty in the Bay area. There are several success stories, including one community college faculty member who is creating a class that will be transferrable to UCB. Using that example as part of the recruitment materials may help attract more community college faculty to the program. If there is a true value proposition for community college faculty, there should be a better chance of recruiting enough participants to fill every available opening.

For graduate students, aside from the typical seminars and graduate courses, the leadership certificate is a way for graduate students and postdocs to learn transferable skills for the next stage of their careers. There are several topical areas that are available: leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship. Nineteen students have completed the leadership certificate since the inception of the Center; 2 have completed the certificate program during Period 8. Of note, graduate students and postdocs are trained in mentoring – particularly with diverse populations - before they become mentors to younger students.

The graduate students are also working on the legacy of the education program of the Center. They have created online videos targeted at high school students, community college students, and graduate students; 48 videos are under development. Additionally, they are writing an e-book targeted at high school seniors on Center research topics that will be hosted on nanohub.org. A draft of the Theme II research topic has been completed. High schools students will be used as reviewers, which is an important step to ensure readability and understandability at that level.

Having graduate students involved in the assessment and selection of candidates for the REU programs and reviewing of REU students' posters is interesting and commendable. Graduate students will gain skills in assessing candidates and giving feedback, which is likely something that they will continue to do throughout their careers.

<u>RECOMMENDATIONS:</u>

- Since the educational efforts are in general quite successful, the SVT recommends that the Center continue and expand its thinking about how to sustain these efforts beyond the life of the Center. There are likely some that could be transitioned to other Centers at Center-partner institutions and beyond, some that could/should be institutionalized at Center-partner sites, either at the institution or system level, and some that could be included in future proposals for support to NSF, other foundations, and corporate partners. The SVT also encourages the Center to consider the knowledge gained in the successful creation and implementation of its education programs as part of its knowledge transfer activities.

- The Transfer-to-Excellence program should be disseminated as such, to a minimum of the Center partner sites as applicable, and more broadly, for example, to other NSF Centers, and perhaps system-wide for the University of California.
- The SVT encourages Center personnel to examine critically their intention to teach STEM pedagogy to participants in the RET for community college faculty. Is this a true need of potential participants? Also of importance is the idea that knowledge transfer is only done from Center personnel to participants, ignoring, perhaps the knowledge participants in the RET have about teaching diverse groups of students. The SVT recommends that this program be reimagined such that there is a clear value proposition for both parties – the Center and community college faculty.
- The SVT recommends using high school teachers as reviewers of the e-book as well as high school students. High school teachers will have an understanding of typical topics covered in high school classes and can give feedback on how the e-book can be explicitly grounded in ideas that high school students already understand, so that the new ideas presented in the book can be more quickly and easily understood.
- The SVT recommends that students involved in the assessment and selection of candidates for the REU programs and reviewing of REU students' posters be trained in how unconscious bias can creep into our assessments of candidates from underrepresented groups, regardless of the steps taken to "blind" the applications.
- The education efforts and activities at the other Center institutions do not seem to be at the same level as at UCB. The SVT recommends that these efforts and activities be replicated on a similar scale at all the participating Center institutions.

Broader Impact: Diversity Plan and Accomplishments to Date

The close integration of the Center's diversity activities with the Center's educational activities is a strength. The proportion of students from underrepresented groups who have participated in the Center's diversity activities is quite high (80% of total, with 44% women and 55% URM).

The NSF-sponsored HBCU REU (Research Experiences for Undergraduates) is an excellent program, particularly when combined with University of California's Bridge to Berkeley program. The REU gives students at HBCUs an opportunity to conduct research at an R1 institution, and the Bridge to Berkeley program improves the successful transition of students from HBCUs to R1 campuses. The HBCU REU program also give students the option of a second summer research experience, which can help participants solidify their interest in research and the topics of the Center.

The E^3S REU program also utilizes the Jolly Model of Student Success and has a very high representation of undergraduate students from underrepresented groups (63%). Additionally, a significant proportion of E^3S REU alumni (73%) are currently in or have graduated from graduate STEM programs, which is a significant impact of the Center.

The presentation of diversity and inclusion related topics at the Center's annual retreat is a notable strength of the Center. It is important for all students and faculty affiliated with the Center to have an understanding of diversity and inclusion, the benefits of having diverse students and faculty affiliated with the Center, and a common language around diversity and inclusion-related topics. It is important that majority groups are fully engaged in diversity and inclusion efforts such that culture of the Center is fully inclusive. This type of knowledge will be important as students launch into the increasingly diverse STEM profession.

The SVT also commends the Center for starting staff/student lunches. While it is very important for students to connect with faculty, it is also important for students to see staff as resources to them, and as a means for changes and improvements within the Center.

The Director of Diversity and Associate Director of Education both travel to attend various diversity-related conferences to create awareness of the Center and its activities. This year, the Director attended the OSTEM (Out in STEM) conference. This is a good addition to the list of conferences previously attended.

The revamped Center website is more reflective of the diversity of the Center, and Center personnel hope that this will enhance the recruitment of students from underrepresented groups to the Center. The SVT commends the Center for updating the website specifically in response to a request from the Center's students and postdocs. Additional efforts to continue to enhance the recruitment of underrepresented groups are ongoing.

While somewhat outside the focus of the Center, the SVT also commends the inclusion of the Director of Diversity in the Graduate Admissions committee for the Electrical Engineering/Computer Science department at UCB. It is hoped that this addition to that committee will help diversify the graduate student body of the department.

RECOMMENDATIONS:

- The diversity efforts and activities at the other Center institutions do not seem to be at the same level as at UCB. The SVT recommends that these efforts and activities resident at UCB be replicated on a similar scale at all Center institutions.
- The SVT notes that students who identify as part of the LGBTQ community are not listed as part of the focus of the Center as stated in the Annual Report (page 95); the SVT recommends that this community be included.

Broader Impact: Partnerships and Knowledge-Transfer Plan and Accomplishments to Date

E^3S has done an excellent job in establishing partnerships in accelerating research, education, and outreach endeavors. The Center continues to invest significant efforts into sharing new knowledge with industry, academia, research labs, and the general public through publications, the E^3S organized Berkeley Symposium on Energy Efficient Electronics, and workshops. As a whole, 19 patent applications and disclosures have been filed so far. The Center members have signed IP agreements and non-disclosure agreements with four large companies. Center members have started 10 companies, which collectively employ more than 1000 people.

Theme I has made significant impact on the fundamental sciences of tunneling devices in general and changed the direction of tunneling FET research world in particular, to include defect states. EAB members believe that the concept of monolithically integrating NEM switches and reconfigurable interconnects above CMOS may truly revolutionize the field of low-voltage reconfigurable integrated circuits. Moreover, theme II appears to be at the most advanced stage to be adopted for machine-learning applications. In the near term, with the demonstration of 10^{15} On/Off cycles of millivolt relay and its associated circuit, these devices could have immediate applications for wireless sensor networks that require ultra-low power consumption. The efforts of developing paper-thin NEM mechanical switches have attracted great interest from industries: a consortium consisting of four large companies has just been established with the potential to take the technology to next level. Related to Theme III, wafer scale III-V/CMOS integration (200 mm wafers) is under way with one startup. Theme 4 has successfully demonstrated an On/Off ratio of 2 via electrically induced picosecond pulses; this opens up the possibility that the magnetic memory element can also be used as a fast-switching logic element, and could provide the needed memory or storage technology for the Center members to pursue the demonstration of reconfigurable interconnect.

RECOMMENDATIONS:

- Continue to pursue IP protection and patent applications.
- Continue to pursue integration with CMOS platform.
- Provide support to graduate students who are seriously considering starting their own companies.
- Continue to engage with large companies to take the technologies developed by E^3S researchers to next level.

Shared Experimental Facilities

Berkeley, Stanford, and MIT have world-class shared facilities for nanofabrication and characterization / imaging. These facilities have a long track record of successful operation (e.g., the Berkeley nanolab recently celebrated its 50th anniversary, and MIT is about to open a new $350M building solely dedicated to nanofabrication and characterization).

E^3S is facilitating access to these facilities for students and postdocs from all Center sites, including in particular for members of FIU and UTEP.

In the past year, there has been strong interest from industry to add ferromagnetic materials to CMOS (project led by Phillip Wong, Stanford in collaboration with Applied Materials, which provided fab services).

RECOMMENDATIONS:

- Sustained institutional support beyond the life-cycle of E^3S (and individual grants in general) is essential to keep access to these crucial facilities available and affordable.

This support may be in the form of space, general infrastructure support, or internal funds. Maintaining or increasing this institutional support is an effective investment.

- The committee encourages further industry collaborations in the coming years.

Value-Added of Center-Mode Operation

The SVT confirms the findings on value-added operation from previous years. The E^3S Center represents a well-organized multi-university effort in investigating energy efficient electronics. The valuable effort to organize leading researchers and manage innovative research and education approaches towards a common and truly challenging goal has been overall successful thus far, and has delivered more than each individual Pl could have done by her/himself. In addition, it is evident that the Center has esteemed leadership, clear organization, well-defined goals, effective integration strategies, thoughtfully-planned and well-executed education and diversity-enhancing plans. The synergy of the faculty members, staff, postdocs, and students from the partner institutions that comprise the E^3S Center enables progress that significantly exceeds what could be accomplished by any single institution. The multi-institution composition greatly expands the range of expertise and experience possible at any single institution, and thereby enhances progress in both research and community building. The integration part is doing a commendable job in bringing the efforts together and providing feedback and guidance on the devices being developed. The cross-fertilization of ideas between the five themes as well as inspiration of projects in one theme due to the progress in another has been a strong value-add of the Center. The Center brings a higher value than the sum of its individual parts as evidenced by its deep integration of research and education, and its commitment to broadening participation of underrepresented groups through workforce development.

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