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

Reply to the National Science Foundation Site Visit Report

Site Visit Date/Venue: January 9-10, 2018 / University of California, Berkeley, CA

The leadership team of the Center for E^3S, on behalf of all its students, postdocs, faculty, and staff, wishes to thank the 2018 Site Visit Team (SVT), the NSF personnel attending the Site Visit, and our program director, Dr. Usha Varshney, for a highly productive and supportive Site Visit. We are grateful for the very positive evaluation of our Center and the recommendation for continued funding. We are particularly pleased with the SVT's recognition of our Center's synergistic multi-institutional approach and the assessment that the "Center is functioning in an efficient and highly productive level".

The Center leadership has reviewed the 2018 SVT report. We have considered all concerns and recommendations by the SVT and are pleased to provide our response below (comments and recommendations of the SVT are given in Italic font).

A. RESEARCH PLANS AND ACCOMPLISHMENTS

1. Nanoelectronics: Theme 1 (pages 3-4):

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

    Response: Given the discovery we made in the initial years of the Center, that the accepted mechanism for a proper functioning tunnel transistors needed to be overhauled, toward the energy filtering mechanism, our goals evolved. Ultimately, we want to find a working technology that could be put into production right away. However, this will require numerous material breakthroughs, and will demand a concerted worldwide materials effort. So far, the E3S Center has been the first to recognize the issues, but our real task is to marshal and persuade decision makers all around the world that our vision is correct. In effect, we are pursuing a grand challenge, and we will need stimulate a world-wide effort to find an electrical switch 100× more sensitive than the conventional transistor.

    Specifically toward period 10, we need to convert field of new transistor switching devices into a field of current-voltage spectroscopy. We need to find the limits of spectral sharpness of band-edges, quantum dots, and other spectral features. Having identified the correct current-voltage methods of measuring spectral line-shape, we will need to persevere to make the spectral shape sharper and sharper to fulfill the practical switch goals. We believe that our remaining work on III-V semiconductors is mature enough to develop the spectroscopy, but that the possibility of practical success will lie with the new semiconductors, the monolayer chalcogenides, and the graphene nanoribbons.

  - *SVT: The stability of superacid surface treatment needs to be better established.*

    Response: We are keenly aware that the chemical treatment approach for improving surfaces is good for obtaining quick results, but that it has always been troubled by long-term reliability, reproducibility and consistency issues. Nonetheless, our chemical approaches toward monolayer chalcogenide treatment and processing are rapidly being adopted by the field, and with chemical understanding, the passivation process will change and become more-and-more robust. Indeed, this was also the early history of the Si/SiO2 oxidation process, where early MOSFET devices were utterly unstable, but now solid–state electronics depends on those interfaces.

- *SVT: 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.*

  Response: Actually, the emphasis now is on the new 2D semiconductors. The Executive Committee discontinued two Co-PI's who had been contributing important information on the III-V semiconductors, but who were not prepared to go in the new direction. We only have one single investigator remaining in III-V's, since we believe that his nanopillar approach can lead us more directly toward the current-voltage spectroscopy approach, which is the next important scientific step in this field.

- RECOMMENDATIONS:
  - *SVT: 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.*

    Response: This is a very sound suggestion, since it forms a sanity check on the tunnel FET concept that everyone assumes. Actually, we have done this model, and so have most of the research groups in the field. With no band-tail the ON/OFF ratio is always excellent, as is the sensitivity. Moreover, the transconductance is adequate.

    The problem in the field is that the experimental devices from around the world all fail to fulfil all the three major requirements simultaneously: Steep response, ON/OFF ratio, and adequate ON-state conductance. We believe that the reason for this failure is that the field has not come to grips with the need for new current-voltage spectroscopic science that would enable us to engineer the band-tail issues, and ultimately to improve them to the point of being competitive with conventional transistors.

  - *SVT: 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.*

    Response: We have made depletion mode devices, and published them, with reasonable good ON/OFF ratio. The inversion mode would show and even better ON/OFF ratio. The new 2D semiconductors are constantly improving as the field learns to make better electrical contacts, and we hope to show those inversion mode results at the next review.

2. Nanophotonics: Theme 3 (pages 4-5)

- CONCERNS:
  - *SVT: The progress on the nano-photoreceiver was not clear.*

    Response: We have reported a comprehensive analysis of the fundamental performance limit of the nano-photoreceiver, including the noise and energy consumption of the CMOS amplifiers and circuits. This result has been published in [K. T. Settaluri, C. Lalau-Keraly, E. Yablonovitch and V. Stojanović, "First Principles Optimization of Opto-Electronic

Communication Links," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 64, no. 5, pp. 1270-1283, May 2017.] The principle has been adopted by a major silicon photonics company, Luxtera. The student, Christopher Lalau-Keraly graduated in May 2017. Otherwise, we would have arranged for him to give a highlight talk in Theme 3. In the coming year, we will have a new postdoc in Prof. Connie Chang-Hasnain's group who will be investigating various implementation of nano-photodetectors.

- RECOMMENDATIONS:
    - *SVT: 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.*

      Response: We could not agree more with this recommendation. This has indeed been the focus of our research in the past year. Due to the extreme sensitivity of the emission wavelength to the dimensions of the device in nanoscale devices, we need single-digital nanometer accuracy in the etched mesa dimension antenna LED emitter. Since this is hard to achieve in university cleanrooms, we have intentionally created an array with small variation of emitter sizes. This will help address the issue.
    - *SVT: 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.*

      Response: In the coming year, we will narrow down the material and device choice of the nano-photoreceiver on InP platform. It is likely to be the same material sysetm as the antenna LED, i.e., III-V InGaAs absorber. This will facilitate the demonstration of the integrated link.
    - *SVT: The SVT recommends that the Center conducts background works for integrating nano-LED and nano-photoreceiver with silicon photonic waveguide during the supporting period.*

      Response: We will also investigate possible approaches for integrating the antenna LEDs and nano-photoreceivers on electronic platforms. This will include, but not limited to, silicon photonic waveguides. Silicon photonics have been widely used for longer optical interconnect between servers through optical fibers. It may not be the natural platform for short-distance links such as on-chip communications. We will investigate various approaches for integrating with CMOS, including incorporating the interconnect as a backend process after a few layers of electrical interconnect. We will report our finding in the next review.
    - *SVT: Continue to engage with silicon photonics industry and to identify niche applications.*

      Response: We thank the panel for recognizing the importance of engaging with silicon photonic industry. We have strong interaction with Luxtera, the leading silicon photonics company co-founded by the PI of the Center. In addition, we also have collaborated with Intel and HP Enterprise labs on novel photonic sources on silicon photonics. Through the interactions, we learned a great deal on the practical considerations, and constraints, of industrial scale processes. We will continue to engage with them.

3. Nanomechanics: Theme 2 (page 5)

- CONCERNS:
  - *SVT: The team has experienced difficult post-processing on CMOS, with a goal to achieve single nanometer gaps between metal lines.*

    Response: One of the inventions made under the E3S Center is the use of tilted ion implantation (TII) to achieve sub-lithographic features dimensions and pitch, as described in P. Zheng *et al*., “Sub-lithographic patterning via tilted ion implantation for scaling beyond the 7 nm technology node,” *IEEE Transactions on Electron Devices*, vol. 64, no. 1, pp. 231-236, 2017 and covered by U.S. Patent application number 15/798,681 filed October 31, 2017. Since ion implantation is routinely used in high-volume IC manufacturing, the TII patterning technique provides a means for the industry to manufacture BEOL layers with features that have sub-10 nm spacing between metal lines. Since a multi-layered BEOL material stack can exceed 1 micron in total thickness, we plan to collaborate with researchers at Lam Research (a member of the E3S Center’s Industrial Research Board) to develop reactive ion etch processes for forming such high-aspect-ratio gaps, as needed.

  - *SVT: Reliability and life-time of switches remain potential challenges for nanomechanics.*

    Response: Prior experimental studies have shown that the endurance of NEM switches improves exponentially with decreasing operating voltage [H. Kam *et al*., "Design and reliability of a micro-relay technology for zero-standby-power digital logic applications," *IEEE International Electron Devices Meeting Technical Digest*, pp. 809-811, 2009] and will exceed one quadrillion cycles at 1 Volt. This already is more than adequate for relay-based microcontrollers in embedded sensor applications to operate reliably for 20 years at 100 MHz clock frequency and 0.01 average transition probability. With 10x reduction in supply voltage (*i.e,* down to 100 mV), endurance will not be an issue for NEM switches. We have found that the most significant reliability issue is increasing contact resistance due to electrode surface oxidation in room ambient conditions; hence we will be studying the effect of the anti-stiction molecular coatings for mitigating this issue, this year.

  - *SVT: It is not clear whether the squitch and the CMOS back end-of-line (BEOL) approaches can be combined before Year 10 ends.*

    Response: We also plan to coat BEOL NEM logic switches with anti-stiction molecular layers to effectively achieve squitches, similarly as already has been done for planar MEM relays, before the end of the E3S Center.

- RECOMMENDATIONS:
  - *SVT: The team should plan experiments to gather additional data on the reliability of molecular coatings in nanomechanical switches.*

    Response: We fully agree with the SVT and are happy to report that testing to characterize the reliability (contact resistance stability) of molecular coatings for electromechanical switches already is underway. We expect to complete a systematic investigation in the coming funding period.

4. **Nanomagnetics: Theme 4 (pages 5-7)**

- RECOMMENDATIONS:
  - *SVT: 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.*

    Response: We fully agree with the SVT. This new discovery opens exciting opportunities for zero-field switching of perpendicular magnetization. Work is currently already pursued in this direction and we hope to be able to report on results in the next funding period.
  - *SVT: 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.*

    Response: This is an excellent recommendation and we will discuss this possibility also with our industrial research partner Applied Materials.
  - *SVT: 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.*

    Response: We thank the SVT for this great suggestion. In fact, we have already discussed further device size reduction in our period 9 plans in the annual report. The suggestion to study the impact of sample fabrication for these ultra-small devices will fit very well with our planned activities.

5. **System Integration (page 7)**

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

    Response: System integration is indeed far advanced for the nanomechanics, nanmagnetics and nanophotonics themes in our Center. The nanoelectronics theme recognized early in the life of this Center that the preferred density-of-states switching mechanism for tunnel field effect transistors demands higher materials interface perfection than ever previously required or achieved in solid-state electronics. In response, the Center, led by Prof. Yablonovitch, made the decision to focus a significant portion of the research effort in the E3S nanoelectronics theme on identifying, synthesizing and incorporating the new two-dimensional materials that promise excellent surface and interface properties and low defect densities. Therefore, research in the nanoelectronics theme is still at the stage of perfecting materials and integrating them into devices, and less at the stage of integrating these devices into systems. However, we anticipate in the last two years of this Center to make progress towards developing strategies on integrating our 2D materials-based devices into larger systems.

- RECOMMENDATIONS:
  - *SVT: The team should seek to demonstrate applications with integrated nanomechanics and nanomagnetics systems.*

    Response: The team has already begun the work on demonstrating the nanomechanical and nanomagnetic circuits in select integrated system applications. In the nanomagnetic theme, we have identified hybrid CMOS-nanomagnetic device integration as a promising direction in enhancing the CMOS system-on-a-chip performance, by utilizing nonvolatile properties of the nanomagnetic structures and incorporating them with CMOS-based storage elements across the memory hierarchy - from register files to caches, allowing a more agile and energy-efficient system-on-a-chip power management. A first step in the direction of the practical demonstration has been done in Philip Wong's group in collaboration with Stojanovic and Bokor groups, in demonstrating a register device with a three-terminal nanomagnetic device integrated on top of the chip.

    In the nanomechanics theme, we have focused in particular on the machine learning inference engine applications, due to their wide applicability and relevance, and lack of competitive CMOS-based hardware structures for deep neural network inference engine implementations for the edge devices (on mobile and internet-of-things platforms). Machine intelligence requires storage of “weights” and efficient multiply operations, essential matrix-vector multiplication elements in linear algebra. The architectures we are pursuing rely on the capability of the underlying device technology to efficiently combine the storage and computation functions, eliminating the energy wasted in communication between the storage and compute units.

    The nano-mechanical and nano-magnetic devices developed within the center can provide the needed functionality for this type of machine learning architecture. We have already made certain inroads towards adopting nanomechanical switches for machine learning. Particularly, we have demonstrated reconfigurable interconnect and reconfigurable computation with embedded storage ([K. Kato, V. Stojanović and T.-J. K. Liu, “Embedded nano-electro-mechanical memory for energy-efficient reconfigurable look-up tables,” IEEE Electron Device Letters, vol. 37, no. 12, pp. 1563-1565, 2016.]) and parallel search capability ([K. Kato, V. Stojanović and T.-J. K. Liu, “Non-volatile nano-electro-mechanical memory for energy-efficient data searching,” IEEE Electron Device Letters, vol. 37, no. 1, pp. 31-34, 2016.]).

    The first step toward practical demonstration has been taken by fabricating a nanomechanic device test chip. BEOL NEMS test chips – comprising a variety of logic and non-volatile NEM switch designs, as well as logic gates – were designed at UC Berkeley and were fabricated at Texas Instruments (65 nm CMOS process), the Colleges of Nanoscale Science and Engineering (CNSE) at SUNY Polytechnic Institute (65 nm CMOS process), and CEA-Leti (130 nm process). Device testing and characterization started before the 2018 NSF Site Visit (and the initial experimental results were presented in one of the student posters) and will be completed within the next several weeks. We expect to implement device design improvements based on the experimental findings, before this summer. We also plan to collaborate with industry partners (TI or GLOBALFOUNDRIES or TSMC) to demonstrate integrated CMOS+NEMS circuits before the end of the E3S Center.

Given these results, these nanomechanical devices are currently at the most advanced stage to be adopted for machine learning applications. Nonetheless, the exciting new developments in our Center, revising the practical applications of magnetism, and hybrid magnetic/CMOS integration suggest that it is also a contender for machine learning. This is due to its potential for nonvolatile and low-voltage/low-energy operation at the throughputs commensurate with edge device operation (Internet of Things, mobile embedded intelligence).

B. EDUCATION PLAN AND ACCOMPLISHMENTS TO DATE (pages 7-9)

- RECOMMENDATIONS:
  - *SVT: 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.*

    Response: As the SVT correctly points out, it is very important for the Center to establish an education legacy, ensuring that our excellent education programs are continued past the sunset of the Center. In this regard, we have already secured extra funding from NSF and the UC Office of the President for our community college programs (TTE and RET) and our REU program (focused on HBCUs). Furthermore, the TTE program has also been "transferred" to an NIH Center at the Berkeley campus, which is supporting five students each summer, and recently also to the Tsinghua-Berkeley Shenzhen Institute (TBSI), which will fund 3-5 students starting in summer 2018. We will continue to reach out to other funding sources, foundations and corporate partners to ensure continuation of our education programs past 2020.

  - *SVT: 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.*

    Response: We fully agree with the SVT that this successful program has the potential to serve as a nation-wide model for increasing community college student involvement and success in research. So far, within the Center, the Transfer-to-Excellence (TTE) program has been solely housed at UC Berkeley, because UC schools are mandated to take a vast majority of their junior transfer students from California Community Colleges. The Center's partner institutions do not have similar setups within their schools and the program development would not be as successful. However, now that the program is fully developed, we are seeking opportunities to transfer the knowledge we have gained over the last seven years to other schools and university systems. A first potential step will be to expand the program to the UT system and we are exploring possibilities with our partner, UT El Paso. We are also looking into further dissemination within the UC system as well as with NSF ERCs. TTE has been and will continue to be highlighted at the annual STC meeting.

- *SVT: 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.*

  Response: We thank the SVT for this excellent recommendation of increasing knowledge transfer from our RET participants into the Center. We will explore possibilities of including more opportunities for RET participants to share their knowledge about teaching diverse groups of students with E3S faculty, students and staff. Regarding the pedagogy workshops, the participants who have been a part of the RET program have all stated that this was very helpful to them in their career development and that they thought that there was a clear need for it within the community colleges. However, we will continue to survey our participants, listen to their needs, and adjust our RET program accordingly.

- *SVT: 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.*

  Response: We thank the SVT for this suggestion. In fact, we have a similar plan already set up: Full drafts of each of the first chapters (nanomechanics) for the e-book will be peer-reviewed within the Center and revised this semester (Spring 2018). Afterwards during the summer of 2018 we will enlist high-school teachers as well as rising seniors in high school to review the draft chapters and provide feedback to ensure that the content is easily understood by high-school students who are interested in STEM.

- *SVT: 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.*

  Response: This is an excellent suggestion and we will implement this in our upcoming summer programs. Diversity director, Kedrick Perry, will work with the education team to organize a training program for all student/postdoc participants.

- *SVT: 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.*

  Response: We agree with the SVT that there is a constant need to update and optimize education efforts at all five of the E3S partner institutions. Since its inception, the Center has tried to implement education efforts at all of the Center institutions on a scale that can be managed by number of E3S faculty at those schools. FIU, Stanford, and UTEP have only one faculty member, and therefore a maximum of one undergraduate student has been hosted at a time. In the case of FIU and Stanford for summer programs, we have tried repeatedly to find a similar program on campus that would be willing to host our students so that they would be part of a cohort and not be isolated as a single student researcher. We have not been able to find any programs that meet our needs in terms of timing and focus. At

UTEP and MIT, we are able to work with the LSAMP program and MSRP at their respective universities, and we host students according to our faculty capacity. Additionally, we participate in the MIT MOSTEC program (high-school program), which takes up a large portion of our education focus at MIT.

C. DIVERSITY PLAN AND ACCOMPLISHMENTS TO DATE (pages 9-10)

- RECOMMENDATIONS:
  - *SVT: 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.*

    Response: The Center thanks the SVT for recognizing the expansive diversity efforts executed. The Center will continue its robust and inclusive efforts to attract a truly diverse student representation. Moreover, we are prepared to share our best practices with other Centers or institutions in order to move the needle overall for STEM graduate degrees.
  - *SVT: 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.*

    Response: Our LGBTQ efforts are relatively new to the Center and we are glad the SVT has recognized them as part of a comprehensive diversity plan. The omission of the LGBTQ community in page 95 of the Annual Report was an oversight and one that will be corrected on the final version of the Annual Report. We take great pride in our efforts to recruit and engage with this vital community and look forward to enhancing our efforts and initiatives to support the LGBTQ community within the Center and beyond.

D. PARTNERSHIPS AND KNOWLEDGE-TRANSFER PLANS AND ACCOMPLISHMENTS:

- RECOMMENDATIONS:
  - *SVT: Continue to pursue IP protection and patent applications.*

    Response: We fully agree with the SVT that pursuing IP protection and patents is of great importance, and the Center has been very active in this area. In fact, since inception of E3S, Center faculty, postdocs and students filed 29 disclosures and patent applications. We will continue to keep our activities in this area high.
  - *SVT: Continue to pursue integration with CMOS platform.*

    Response: We have already ongoing efforts regarding integration with CMOS platforms. For example, a first practical demonstration has been done in Philip Wong's group in collaboration with Stojanovic and Bokor groups. Together, they demonstrated a register device with a three-terminal nanomagnetic device integrated on top of a CMOS chip. We expect these integration efforts to intensify over the next two years.
  - *SVT: Provide support to graduate students who are seriously considering starting their own companies.*

    Response: This is a great suggestion by the SVT. We are happy to report that E3S has become a member of CITRIS (Center for Information Technology Research in the Interest of Society) in the last year. Therefore, our students and postdocs have now access to the entrepreneurial resources offered by CITRIS, including the CITRIS invention ecosystem, which includes competitive seed funding, specialized testbeds, Marvell Nanofabrication Laboratory, CITRIS Invention Lab, and the CITRIS Foundry startup accelerator.

- *SVT: Continue to engage with large companies to take the technologies developed by E3S researchers to next level.*

  Response: We will certainly follow this recommendation by the SVT. E3S is in an excellent position having industry heavyweights IBM, Intel, Lam Research, Applied Materials and HP Enterprise as part of our Industrial Research Board. We will continue our strong interactions with these companies, seek their input and advice regarding E3S technology transfer, and explore future long-term collaborations and joint projects.

E. SHARED EXPERIMENTAL FACILITIES:

- RECOMMENDATIONS:
  - *SVT: Sustained institutional support beyond the life-cycle of E3S (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.*

    Response: We fully agree with the SVT on the importance of sustained institutional support. As was also emphasized by senior administrators from all of the five partner institutions in the conference call on the second day of the Site Visit, E3S enjoys full institutional support and benefits from space and infrastructure support, as well as internal funds provided by all five institutions.

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

    Response: We thank the SVT for this recommendation. We agree that while we already have excellent industry partners, looking beyond the duration of the Center, it will be beneficial to engage in additional industry collaborations. In fact, we have started to build strong relationships with two important companies: TSMC and GLOBALFOUNDRIES. This summer, we invited TSMC to visit the Center, give a presentation, and meet with faculty, postdocs and students. We were fortunate that a group of TSMC researchers and executives accepted our presentation, including Dr. Jack Sun (TSMC Chief Technology Officer and Vice President for Research & Development). In addition, we have started collaboration with GLOBALFOUNDRIES (nanomechanics theme) and representatives were invited guests and speakers at our 5^{th} Berkeley Symposium this fall.

We hope to have considered all concerns and recommendations by the 2018 SVT. In addition, Center Director, Prof. Eli Yablonovitch has instructed each Theme to convene a discussion on the comments we received at the Site Visit and to analyze potential impacts on future research plans.

In case the SVT has any additional questions, please contact either Center PI, Prof. Eli Yablonovitch (eliy@eecs.berkeley.edu), or executive director, Dr. Michael Bartl (mbartl@berkeley.edu).

The entire Center for E^3S again thanks the 2018 Site Visit Team and NSF personnel for the constructive critique, helpful comments, excellent recommendations, and continued strong support of our Center.