NSF Future of Semiconductors and Beyond Workshop

Materials, Devices and Integration

2021

Final Report

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A virtual workshop was held March 1, 2, 8, and 9, 2021 to consider the most impactful paths for future research in semiconductor materials, devices, and integration. The workshop was organized in response to pending U.S. legislation, including the Endless Frontiers Act[1], the Chips for America Act[2], and the American Foundries Act[3], all intended to promote leadership in electronics technology and semiconductor manufacturing. This report is directed to the workshop sponsor, the NSF Civil, Mechanical and Manufacturing Innovation (CMMI) Directorate, to assist program planning and visioning. Best opportunities in semiconductors, devices, electronic materials integration, and manufacturing are summarized in this report. Four topical areas were addressed in the workshop: (1) Harnessing electronic phases and phase transitions, (2) Engineering heterogeneous semiconductor structures, (3) Extending device frontiers, and (4) Advancing organic/biodevices - sensing, stimulation, and communication. This report recommends research directions, programs, and provides motivation for continued investment in semiconductor materials, devices, and related technology.

NSF Future of Semiconductors and Beyond Workshop: Materials, Devices, and Integration

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1. Intellectual Merit

Semiconductors are at the core of the electronics and photonics that underpin many aspects of modern life: computing, wireless communication, transportation, medical diagnostics, artificial intelligences and the internet. Semiconductors have permeated nearly every corner of the human social network. American leadership in semiconductor technology is essential to the U.S. technology sector and to the economy. The Future of Semiconductors and Beyond Workshop served to consolidate a collective understanding and national vision for directed research in semiconductor science and technology.

2. Broader Impact

The workshop brought together thought leaders from universities, industry, and government to consider the future of semiconductor materials, devices, and integration. The virtual workshop captured wide participation (656 registrants), including faculty, students, industry leaders, and government stake holders. The presentations were recorded ahead of the meeting, allowing the meeting to focus on discussion. The presentations remain available to workshop registrants at https://nsf-fosworkshop.nd.edu/. The workshop enabled wide ranging discussions about where the U.S. could be in ten years with thoughtful investment.

3. Conference organization and executive committee. The committee is listed below. Heidi Deethardt, Notre Dame, handled registrations and the logistical aspects of the virtual meeting with ND Studios.

April Brown (Electrical and Computer Engineering, Duke University) - semiconductor growth, solid-state materials and devices for electronics and optoelectronics, applications

David Chow (Chief Science Officer, HRL Laboratories, Malibu) - Semiconductors, leading edge microelectronics technology, emerging applications, systems

Evelyn Hu (NAE, NAS, Applied Physics and Electrical Engineering, Harvard) - optical and electronic materials, materials integration, nanoscale photonic devices, quantum device technologies

Debdeep Jena (Electrical and Computer Engineering, Materials Science and Engineering, Cornell University) - semiconductors, dielectrics, superconductivity, emerging device phenomena, lasers, power devices

Alan Seabaugh, committee chair (Electrical Engineering, University of Notre Dame) - Transistors/memory, ferroelectrics, ionic polymers, integration, circuits

A preceding workshop, entitled "NSF Workshop on Future of Semiconductors and Beyond: Devices & Technologies," organized by Prof. Kang Wang (UCLA) was held February 8, 9, 17, and 18, 2021. Both workshops were aimed to promote discussions in advancing U.S. leadership in electronics, however the organizing committees were different. The topical areas for the two meetings were chosen so as not to overlap.

4. Technical Program and Speakers

The technical program follows on the next two pages. All talks were prerecorded. The keynote presentations were played on the day of the meeting. The panelists supplied prerecorded talks which were available one-week prior to the meeting. A prerecorded two-minute summary of the panelists presentations was played on the day of the meeting. Panelists were asked to consider the following questions, pertinent to their areas of expertise: (1) What are the greatest scientific challenges holding back progress? (2) What technical directions will provide the greatest scientific/technical advances? (3) What is the greatest misconception you face that needs to be dispelled? (4) If you are successful, who will care? Participants also typed questions into the live webinar to be asked by the moderator.

Technical program
NSF Workshop on the Future of Semiconductors: Materials, Devices, and Integration

Session 1: Monday, March 1, 2021 - Harnessing Electronic Phases and Phase Transitions

Moderators: Debdeep Jena (Cornell) and David Chow (HRL Laboratories)

Noon Opening Remarks: Alan Seabaugh (Notre Dame), Dawn Tilbury and Robert Stone (NSF)
12:15 Keynote: The Rise of Moiré Quantum Matter, Pablo Jarillo-Herrero (MIT)
12:50 Q&A
1:00 Keynote: Integrating Ferroelectrics with Semiconductors, Susan Trolier-McKinstry (Penn State)
1:35 Q&A
1:45 Break
1:55 Panel discussion 1: Future Phase-transition Materials and Physics
  - First-principles Design, Chris G. Van de Walle (UC Santa Barbara)
  - Topology Materials Science, Claudia Felser (Max Planck Dresden)
  - Challenges and Opportunities in Spintronics, Dan Ralph (Cornell)

2:55 Break
3:00 Panel discussion 2: Future Phase-transition Devices
  - What Spintronics Tells Us About Future Information Processing, Hideo Ohno (Tohoku Univ)
  - Future of Quantum Computing: Heterogeneous Quantum Devices, Jason Petta (Princeton)
  - Novel Materials for Electronic Devices, Susanne Stemmer (UC Santa Barbara)
  - Transition Metal-based Materials for Novel Hybrid Coupled-phenomena Device Platforms, David J. Meyer (Naval Research Laboratory)

4:00 Discussion
4:30 Wrap-up

Session 2: Tuesday, March 2, 2021 - Engineering Heterogeneous Semiconductor Structures

Moderators: Evelyn Hu (Harvard) and April Brown (Duke)

Noon Opening Remarks: Alan Seabaugh (Notre Dame) and Tom Kuech (NSF)
12:10 Keynote: New Strategies in Nanoelectronic 3D Heterogeneous Integration
Christopher Hinkle (Notre Dame)
12:45 Q&A
1:00 Keynote: Abandoning Perfection for Semiconductor Technologies
David Awschalom (University of Chicago)
1:35 Q&A
1:50 Break
2:00 Keynote: Metasurfaces as Heterogeneous Nanostructured Materials for Multifunctional Flat Optics: From Components to Cameras, Federico Capasso (Harvard)
2:35 Q&A
2:50 Break
2:55 Panel discussion: Rethinking Heterogeneity
  - Why the Nitrides Will Remain Dominant for Decades to Come, Umesh K. Mishra (UCSB)
  - Compact and Integrable Free-electron Light Sources, Marin Soljačić (MIT)
  - Advancing Photonics with Machine Learning, Sasha Boltasseva (Purdue)
  - Hybrid Semiconductor Heterostructures: Harnessing Topology, Broken Symmetry, and Heterogeneity for Future Science and Technology, Nitin Samarth (Penn State)
  - Scalable Semiconductor Quantum Systems, Jelena Vuckovic (Stanford)

4:00 Discussion
4:30 Wrap-up

Session 3: Monday, March 8, 2021 - Topic: Extending Device Frontiers
Moderators: David Chow (HRL Laboratories) and Debdeep Jena (Cornell)

Noon Opening Remarks: Alan Seabaugh (Notre Dame) and Don Millard (NSF)
12:10 Keynote: Electronic Materials and Device Research for the Coming Decade
Bobby Brar (Teledyne Technologies)
12:50 Q&A
1:00 Keynote: Electromagnetic Spectrum Control Through Material and Device Innovations
Dev Palmer (DARPA)
1:40 Q&A
1:50 Break
2:00 Panel discussion 1: Transduction and Reconfigurability

- Extending Device Frontiers – Materials Integration, Transduction, and Reconfigurability, Nian Sun (Northeastern)
- Quantum Transducers: Materials, Devices, and Heterogeneous Integration, Hong Tang (Yale)
- Phase-change Materials for Next-generation Reconfigurable Nanophotonic Structures Ali Adibi (Georgia Tech)
- Emerging Needs for Electromechanical Transducers, Dana Weinstein (Purdue)

3:00 Panel discussion 2: Deep-UV and IR Materials and Devices

- (AlGaBIn)N Based Materials for UV Emitting Photonic Devices, Steven Denbaars (UCSB)
- Ultrawide Bandgap Semiconductors and DUV Devices, Grace Xing (Cornell)
- The Future of Quantum Semiconductor Science and Technology for IR Emitters and Detections, Manijeh Razeghi (Northwestern)
- Frontiers of Infrared Semiconductor Lasers, Jerry R. Meyer (Naval Research Laboratory)

4:00 Discussion
4:30 Wrap-up

Session 4: Tuesday, March 9, 2021
Topic: Advancing Organic/Biodevices - Sensing, Stimulation, and Communication
Moderators: April Brown (Duke) and Evelyn Hu (Harvard)

Noon Opening Remarks: Alan Seabaugh (Notre Dame) and Shekhar Bhansali (NSF)
12:10 Keynote: Emerging Research Opportunities in Bio-Integrated Semiconductor Devices
John A. Rogers (Northwestern)
12:45 Q&A
1:00 Keynote: Skin-inspired Organic Electronics: New Opportunities and Seamless Interface with Biological Systems, Zhenan Bao (Stanford)
1:35 Q&A
1:50 Break
2:00 Keynote: Building Things in Brains: Chemistry Construction Projects for Analysis and Discovery in Neural Systems, Karl Deisseroth (Stanford)
2:35 Q&A
2:50 Break
2:55 Panel discussion: Opportunities and Challenges in Biodevices and Organic Semiconductors

- Emerging Opportunities in Organic Optoelectronics, Stephen Forrest (Univ. Michigan)
- Digital Health, Geoffrey S. Ginsburg (Duke)
- A Case for Convergence Microscopy, Kimani C. Toussaint, Jr. (Brown)
- Engineering of Functional, Stable, Biotic/abiotic Interactions, Albena Ivanisevic (Army Research Office, NC State)

4:00 Discussion
4:30 Wrap-up

5. Workshop Metrics – Registration and Participation

The workshop had 656 registrants and attendance was spread out over the 4 topical sessions. Participation was measured over the course of the afternoon sessions as shown in Fig. 1. Audiences varied over the four days. Keynote talks were played in the first 1.5-2 hours and discussion proceeded during the rest of the afternoon.

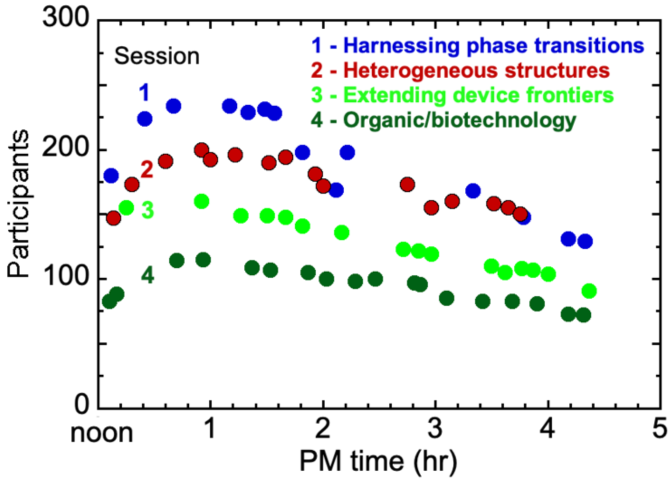

Figure 1. Number of workshop participants versus time for the four workshop sessions. NSF Workshop on the Future of Semiconductor: Materials, Devices, and Integration, Zoom Webinar, March 1, 2, 8, and 9, 2021, corresponding to sessions 1, 2, 3, and 4.

6. Rationale and Motivation for the Workshop Topics

6.1 Session 1 – Harnessing Electronic Phases and Phase Transitions

The Venn-diagram of semiconductor electronic phases has rich intersections with other electronic phases. For example, semiconductors exist that are simultaneously ferroelectric, superconducting, ferromagnetic, or that can be electrically controlled to transition among these states. These electronic properties are inaccessible in elemental and binary III-V semiconductors. Material phase transitions can occur between hybrids of electrons and phonons in strongly coupled semiconductor acousto-electric structures, or between electrons and photons in strongly coupled light-matter hybrids. A wide range of new devices can be expected to emerge in the development of semiconducting materials which harness phase transitions.

For example, in 2011, hidden phases were discovered in $HfSiO_2$[4] and $HfZrO_2$[5] formed by atomic layer deposition (ALD), where the addition of Si or Zr changes the insulator into a ferroelectric. ALD is widely employed in semiconductor foundries, allowing device opportunities for memory and logic to be advanced at a rapid pace. In 2019, ferroelectricity was demonstrated in two semiconductors, ScAlN[6] and two-dimensional In_2Se_3[7], revealing that semiconductors can possess a ferroelectric property. Several semiconductors such as diamond, MoS_2, and even graphene exhibit superconducting phases, some emerging from structure (such as in twisted bilayer graphene). Unlike in traditional materials, in semiconductors, ferroelectricity and superconductivity phases can be turned on and off by the field effect, carrier injection, or with light! These electronic phases of matter include correlated phenomena (e.g. ferroelectricity and ferromagnetism) and offer opportunities to circumvent bottlenecks that exist today in memory, logic, and communication systems. With cloud computing and a data-center-based computing future, cryogenic operation is being reconsidered for computing (both classical and quantum). Low temperature adds to the device opportunities.

The phase transition itself is marked by energy absorption or release and, if efficiently harnessed, could be used to create new low-voltage, steep subthreshold swing transistors and selectors. Structural and chemical phase transitions, coupled with electronic phases can occur at subnanosecond speeds, making them highly relevant for device technology applications. In short, devices operating about these phase-critical points can bring new functionality and break traditional device limits.

Starting from Ge in the 1940s, to Si, III-Vs, III-nitrides, SiC, wide bandgap diamond, BN, and AlN, semiconductors have advanced from narrow bandgap to wide bandgap (0.35 (InAs) 0.67 to 5.5 eV) to allow applications ranging from computing to power amplifiers to lighting. Wide bandgap materials typically have far higher structural strength than lesser bandgap semiconductors, and sustain much higher strains. Under ultrahigh pressures, superconductivity has been achieved (during COVID!) at room temperature[8]. A diamond anvil (which is itself a semiconductor) was crucial to applying the ultrahigh pressure needed to achieve a room-temperature superconductor. How will the light-atomic mass semiconductors themselves behave under such perturbations? Can much higher strains be applied to semiconductors than have previously been used, in turn revealing a rich array of yet-undiscovered phase transitions, and new physical phenomena?

6.2 Session 2 – Engineering Heterogeneous Semiconductor Structures

Interface defects, surface imperfections, and background impurities often limit device and system performance. Three-dimensional scaling and thermal management are adding new challenges in modern device development, and process optimization must often be simultaneously managed on multiple orthogonal surfaces. To address this challenge, atomic resolution characterization techniques and first-principles simulations are providing insights to possible new material performance that might address these challenges. Discoveries made in this space are needed to seed new manufacturable approaches, extend existing device capabilities, and lead to the realization of new device concepts.

For example, the tunnel FET (TFET) can outperform other transistors at low voltage. However, due to the stringent process requirements, a manufacturable process has never been realized. The source-channel tunnel junction and the gate-oxide interface must be simultaneously optimized to create an abrupt, heavily-doped tunnel junction with precise orthogonal alignment of the gate oxide and the tunnel injector. Critical to the operation is a subnanometer equivalent-oxide-thickness, low interface trap density to thwart defect-assisted tunneling, and low gate leakage to provide low off-state current. This level of control has not been solved in a process suitable for very large scale integration (VLSI).

Devices based on two-dimensional semiconductor materials have encountered similar limits to manufacturability. There remain challenges to deposition in wafer-scale VLSI formats with resulting sufficient mobility to enable transfer to industry. Industry acceptable methods to dope these materials are needed. Basic technologies for formation of *p-n* junctions, ohmic contacts, and reliable methods to deal with a surface that has no dangling bonds remain unsolved problems.

Devices for control of qubits through defect states represent another set of process challenges which must be solved for quantum computing, networks, and sensing. In these devices the qubits must be deterministically placed, while controlling the proximal defects. Using wide-bandgap host materials, defects as qubits benefit from the electronic isolation provided by the host material and the ability for optical interaction that these systems enable. One can envision piezoelectric, ferroelectric, or other coupling used in the sensing and control of qubits.

Interfaces have played an important role in optimizing thermoelectric devices in low-dimensional structures, where the interface can partly decouple thermal and electrical conductivity, thus increasing the thermoelectric figure of merit.[9]

In a similar vein, surface states of semiconductors were formerly considered to be uncontrollable. Recent discoveries of ordering of surface states to form topological surface bands are uncovering a rich range of transport phenomena in semiconductors where spin and momentum locking generates natural spin-polarized currents. Some of the most efficient spin-torque generators today for spin-transfer torque (STT) and spin-orbit torque (SOT) random access memory (RAM) are based on topological spin-bands on the surface of semiconductors[10]. This line of investigation is expected to lead to new transport phenomena and device applications for semiconductors with large spin-orbit coupling.

Multifunctional metamaterials. Metamaterials, often composite assemblies of diverse materials, are engineered to exhibit properties not found in naturally occurring materials. There have been exceptional demonstrations of powerful new, polarization-sensitive, wavelength-sensitive materials that enable optical shaping and processing in planar form, allowing for a natural and powerful device integration.[11] Can these materials be extended to form integrated phononic-photonic-microwave materials, to improve energy-efficiencies, filtering capabilities, etc.? Can self-correcting mechanisms be built into the processes, to mitigate materials defects? Some of these concepts are already being explored with metamaterial-based approaches. In the emerging area of *topological photonics*, materials are being engineered that demonstrate directional guiding of optical waves without external control, and robust transmission of information even in the presence of defects.[12]

6.3 Session 3 – Extending Device Frontiers

This topic addressed device technology approaches to extending system performance. The aims in this area were to frame the device and system grand challenges that could be met through material and structure innovations. Candidate areas for innovation included:

1) Reconfigurable systems enabled by devices and materials that can be rapidly reconfigured to dramatically change system-level characteristics. A recent example is chalcogenide phase change materials, which have been used to make reconfigurable RF systems and reconfigurable optical structures.[13,14]
2) Novel devices for transduction of one form of physical energy to another. Recent examples include mechanical antennas enabled by multiferroic materials, wide bandgap acoustic devices, and MEMS devices for position, navigation, and timing control.[15,16]
3) Spectral extensions of optoelectronic devices to the UV and deep UV, as well as extending throughout the infrared spectrum with high efficiency and manufacturing compatibility (low cost). Device types may include light emitters (lasers/LEDs), modulators, photonic combs, nonlinear optics devices, and detectors.[17,18]
4) Power conversion devices and materials (including novel magnetic materials) to drive reduced size in high efficiency converters needed for sustainable energy generation, energy storage, and electrification systems[19,20]
5) Electronic and optoelectronic devices tailored for use in medical and biological applications (distinct from topic 4, which targets biocompatible materials and devices)
6) Real-world (analog) information processing devices to reduce data overload of networks and systems by processing information at the front end / sensor
7) Electronic materials and devices that are enabling for future digital and information processors, which may include selectors, non-volatile analog weight storage devices, materials for 3D integration, and back-end-of-line active devices.[21]

6.4 Session 4 – Advancing Organic/Biodevices: Sensing, Stimulation, & Communication

Electronic and photonic systems that can be formed on flexible substrates can substantially broaden the application space for semiconductor materials and devices. Earlier approaches explored thin-film semiconductors on low-cost substrates, such as metal foils, plastic sheets or paper.[22] More recent approaches achieve a fuller integration of organic and inorganic materials, incorporating various organic, polymeric and elastomeric materials, as well as hydrogels.[23,24]

The combination of small-scale semiconductor electronic and photonic devices integrated within thin, compliant and stretchable form factors has advantages for applications of physiological monitoring and diagnosis, by virtue of the more intimate contact of multiple devices with the biological system. In fact, researchers have reported on *Epidermal Electronics*, devices that can be laminated onto the skin, attached through van der Waals forces,[25] and electronics mounted on dissolvable silk fibers, in order to provide direct, "non-invasive" contact and measurement of biological tissue.[26]

These demonstrations raise questions about future possibilities. Do compliant, stretchable electronic "fabrics" provide new means of control and sensing (e.g. the use of strain)? Can these materials be engineered to demonstrate self-healing properties? Are there new information channels possible (e.g. via ionic conduction)? Does the compliant geometry, through its stretchability and foldability suggest new architectures for signal routing? Can these new architectures form the basis of more efficient computation or communications schemes? Beyond biological applications, are there other areas of sensing, computation and imaging that would benefit from using organic, compliant electronic systems?

Another example of recent advances in semiconductor/biological interfaces is the formation of a CMOS nanoelectrode array comprising 4096 nanoscale electrodes that allows extracellular recording of direct synaptic signals.[27] This achievement raises new questions. What are the challenges in controlling interfaces and surfaces in inorganic (semiconductor), biological (wet) hybrid systems? What future electronically controlled biological systems might result?

The first electrically-injected deep-UV laser, operating at room temperature was demonstrated in December 2019.[28] These diode-lasers and LEDs are poised to revolutionize diagnostics and therapeutics of bacteria and virus species at unprecedented levels of specificity. Development of semiconductor photon sources and detectors at the level of single photons have the potential to take biodetection and specificity to levels that are currently only achieved in communication systems.

How do we move from the training of neural networks to the creation of systems that incorporate learning and distributed memory, have a system-level resilience, and naturally reinforce particular communications pathways in the way similar to biological systems? What are the key problems to solve and in what systems? What are the grand challenges for sensing, cell communication, diagnostics, and control? Can we identify focus areas, e.g., healthcare and diagnostics, the environment, homeland security?

7. Findings from each of the Sessions

7.1 Session 1 Findings - Harnessing Electronic Phases and Phase Transitions

There continue to be new and extraordinary phenomena being uncovered in semiconductors. Keynote talks by Pablo Jarillo-Hererro, on twisted two-dimensional van der Waals materials[29], and Susan Trolier-McKinstry, on ferroelectrics and semiconductors, showed that materials and device opportunities are continuing to expand by the discovery of new physical properties suitable for the implementation of electronic logic, memory, and communication. The design of new materials by consideration of topological properties was described by Claudia Felser[30]. The application of first principles computations by Chris van de Walle reveal that many intriguing experimentally realizable phenomena, such as polarization discontinuity, ferroelectricity, etc., emerge when structurally mismatched materials are joined in alloys or interfaces. A major finding of the session was that new materials spaces with unexpected physical behavior have dramatically emerged in the last decade. Discussion ranged from how to efficiently translate the physical phenomena that is observed in these new materials to applications, to what is the vision for creating new materials, and to particular questions such as how to best characterize quantum entanglement in large systems? These opening panel sessions provided a broad perspective for the rest of the workshop.

7.2 Session 2 Findings - Engineering Heterogeneous Semiconductor Structures

Discussions made in Session 1 revealed the richness of electronic phases that can often co-exist in the same multi-element materials, providing ferroelectric, superconducting, ferromagnetic magnetic behavior in the same platform material. Progress in this area holds promise for the creation of multi-functional device and system behavior. The two-dimensional materials discussed in Session 1, such as the Transition Metal Dichalcogenides (TMDs), can produce high quality heterostructures through layering, and this theme re-appeared in Session 2, This session continued to explore the possibilities of multi-functional devices and systems, possibly through the integration of heterogeneous materials, but mitigating the traditional penalties of the traps, impedance mismatches or other constraints that traditionally accompany such heterogeneity.

7.2.1 Insensitivity to Lattice-Matching

Materials that exhibit high performance and yet are relatively insensitive to lattice-matching with a substrate, may manifest fewer dislocations and defects. Beyond possible layering techniques for two-dimensional TMDs, mentioned above, lattice-insensitive materials might be amorphous, or like *entropy-stabilized oxides* accommodate multiple elemental components, enable tunability in composition, and therefore in functionality.

7.2.2 Low-temperature and Chemically-Selective Processes

Low temperature processes mitigate the effects of thermal mismatch in the integration of heterogeneous materials, and in the fabrication of device structures. Low temperature processes can ease the compatibility constraints when merging technology platforms.

Chemical selectivity, control over thickness and composition in deposition or etching of materials are highly desirable for heterogeneous structures; further development of appropriate chemical precursors can extend the applicability of these processes.

7.2.3 Building Heterogeneity from the Hierarchy of Size Scales

Several speakers in Session 2 made important points about heterogeneity achievable at appropriate “scales”:

1. Discrete geometrical structures at a small enough size scale (below the wavelength of an interrogating signal) can form *metamaterials* that can demonstrate differing functions according to incident wavelength and polarization.
2. At appropriate size scales, photon, phonon, spin and magnon energies can become commensurate, allowing for efficient energy transduction, and presaging new device approaches.
3. Atomic or molecular-size material defects or impurities can provide new quantum-coherent information modalities.

While keynote speaker David Awschalom advocated "embracing dislocations, disorder, and defects," others focused on the defect-tolerant possibilities of new topological materials.

7.2.4 New Methods for Multi-Modal Characterization

A key need in development of new robust, and integrable materials is multi-modal characterization, *in situ* and *in operando*, as pointed out by workshop keynote speaker Chris Hinkle. In some cases, such characterization needs to be done at the *atomic scale,* and new, high-resolution fabrication instrumentation will be required; David Awschalom termed this "extreme scale fabrication".

7.2.5 New Computational and Simulation Tools

In developing new robust, integrable materials, as well as new device architectures and geometries, Session 2 speakers pointed to the importance of new computational and modeling strategies. Development of new materials having extended functionality will require "data mining and physics-based machine learning" (Hinkle). Complex device geometries matched to tolerances in the device fabrication will require "co-design" strategies, (Federico Capasso and Sasha Boltasseva). The optimal realization of devices within systems benefit from new design strategies, such as the "inverse design" approaches used by Jelena Vuckovic and others.

7.5.6 The Importance of Sustained Investment

Speakers also noted the importance of sustained investment in already-identified materials whose full functionality and applications have been successful and are still evolving. As scientific investment can produce new technologies, it is equally true that the full pursuit of a technology into the realization of an embraced device technology, can itself reveal nuances of the science. Important resources for these studies comprise a different means of *characterization*, those related to probing device reliability and benchmarking.

7.3 Session 3 Findings – Emerging Device Frontiers

Over the past few decades, a deep understanding of the band structure and charge transport mechanisms in established semiconductor heterostructure materials has enabled incredible advances in electronic and optoelectronic devices. Basic elements of this understanding have been captured in commercial simulation packages that are used by engineers developing new high frequency RF transistors, photonic devices, and integrated circuits. In recent years, more advanced, specialty device design and simulation capabilities have been developed within the semiconductor community to tackle particularly challenging problems for high performance devices that may feature high charge densities, high electric fields, and carriers in multiple k-space valleys[31,32]. Several recent DARPA Programs[33] (DREaM, T-MUSIC, MOABB, LUMOS) are using these capabilities to push the bounds of electronic and optoelectronic device technology based primarily on existing semiconductor materials. However, new materials, including ultra wide bandgap materials, narrow bandgap materials, materials for transduction of real-world signals to the digital world, materials for quantum transduction, and ferroic materials, offer the potential to create new classes of devices with important systems ramifications. As new materials emerge beyond established semiconductors, there will be a significant need for theoretical understanding of relevant physics, e.g., band structure, scattering, transport, generation/recombination, to fully exploit the properties of these materials. Session 3 explored several classes of new device frontiers that are emerging, enabled by these electronic materials advances.

7.3.1 High Frequency Electromechanical Transduction

Successful implementation of electromechanical transduction in the mm-wave regime requires several material and device challenges to be addressed, as outlined by Dana Weinstein. First, the demand for ultra-wide-band communication necessitates the development of high-k2 (large piezoelectric coupling) materials whose thickness can be reduced down to tens of nanometers and exhibit low dielectric and viscoelastic losses. Ferroelectric materials under investigation for memory devices in CMOS are promising candidates for this, including but not limited to HZO, Si:HfO_2, and ScAlN. 2D van der Waals materials with large piezoelectric coupling may also be good contenders. More established platforms including GaN and $LiNbO_3$ also offer a path to mm-wave electromechanical systems, arguably with lower barrier to entry given their maturity. However, these materials must be aggressively scaled in dimension, requiring innovation in growth and bonding processes. All these thin film options require fundamental material development, characterization, and optimization, along with new transducer and device design to best leverage their individual benefits. Electrode materials will need to be carefully considered to ensure high conductivity with minimal mass loading and viscoelastic losses.

Second, large tunability in frequency and bandwidth alongside low-loss intrinsic transducer switching are highly desirable for next generation *ad hoc* radio communication requiring spectral scavenging. Ferroelectrics pose a unique property toward this end with voltage-dependent polarization and permittivity, opening doors for built-in tuning of each transducer. Additionally, suspended thin-film membranes have repeatedly demonstrated large frequency tuning when deformed, due to nonlinear elastic properties. This property could be leveraged for extending the tuning range but must be co-optimized with power handling requirements at the system level. Third, recent achievements in acoustoelectrics present an emerging opportunity for scaling electromechanical transducers to the mm-wave operation. This interaction between a strong piezoelectric material (e.g. $LiNbO_3$) and a semiconductor (e.g. GaN, InGaAs, Si) can result in wave amplification, nonreciprocity, and velocity shift which enable more complex electromechanical signal processing. Additionally, the effect is substantially more pronounced in the mm-wave regime, making possible electromechanical amplifiers, switches, phase shifters, circulators, oscillators, correlators, and more. Development of material platforms addressing thermal management, power consumption, and active device integration, along with device design to realize and optimize these various mm-wave building blocks are needed for broad implementation of these components and systems.

7.3.2 Phase-Change Materials for Reconfigurable Circuits and Systems

Phase change materials, as discussed by Ali Adibi, (mostly chalcogenides) have been demonstrated as elements for reconfiguring both RF systems (as non-volatile RF switches) and optical frequency selective surfaces (as individually addressable switching elements). These materials display a large change in their optical properties upon transition between amorphous and crystalline phases and are promising candidates to miniaturize fundamental reconfigurable nanophotonic building blocks, such as phase shifters, delay lines, and tunable elements, that are essential for a large range of applications including communications, quantum photonics, computing, imaging, and ranging. However, significant opportunities remain, requiring the development of improved materials and integration processes. Specifically, it may be possible to realize miniaturized reconfigurable integrated photonic devices, such as phase shifters for chip-scale LIDAR systems, spatial light modulators, and beam control elements. Challenges for phase change materials that must be addressed to realize these goals include dramatically reducing optical loss, improving switching speed to the microsecond range, and integration technologies enabling rapid addressing of large numbers of elements.

7.3.3 Ferroic Materials and Devices

In the past decade, as discussed by Nian Sun, we have witnessed rapid progress on the integration of piezoelectric materials and their MEMS/NEMS devices on Si microelectronics, and integration of magnetic materials on Si for integrated power supply on chip (PWRSoC), and RFIC, new magnetoelectric materials, and devices on Si microelectronics. At the same time, we have seen the rapid development of magnetic printed circuit boards with their relative permeability improved from 1 to 100. The integration of these magnetic and magnetoelectric materials and devices provide great challenges as well as opportunities for the future of semiconductors and the electronics industry.

The challenges on the integration of ferroic (magnetic, ferroelectric, and magnetoelectric) materials and devices on semiconductors include (1) integration of new metallic magnetic materials and devices (non-memory related applications), which are on magnetic materials with high piezomagnetic coefficient, high magnetostriction constant, high permeability, low loss tangent; (2) integration of ferrites, including spinels, garnets, hexaferrites, at a low temperature < 450 °C, low loss tangents, and large thicknesses; and (3) integration of magnetoelectrics for achieving a strong magnetoelectric (ME) coupling at a low temperature with a low loss tangents, and new materials for realizing strong ME coupling. The opportunities for the integration of ferroic (magnetic, ferroelectric, and magnetoelectric) materials and devices on semiconductors are enormous, including electronics with reduced SWAP-C (size, weight, and power consumption, cost) and improved performance of the electronic systems. In particular, integrated magnetic materials, such as low-cost spin-spray-deposited fully-dense and low-loss ferrite materials, on semiconductors and PCBs (printed circuit boards) enable ultra-compact and power-efficient power supply on chip (PWRSoC), and power supply in package (PWRSiP). Thick magnetic PCBs with an unprecedented high relative permeability of >100 for operations between DC~400 MHz have been reported, which outperform conventional ferrites or state-of-the-art magnetic PCBs with one order of magnitude enhanced permeability, which enable ultra-compact antennas and electronics with significantly reduced SWAP-C and enhanced performance.

7.3.4 Quantum Transduction

Although practical quantum computing and quantum communication systems remain a significant and long term challenge for the scientific community, important investments are being made in fundamental elements that will be needed for these systems, including multiple qubit systems and entangled photon systems. As discussed by Hong Tang, hybrid quantum networks rely on faithful quantum state transfer between disparate physical elements operating at dissimilar frequencies and hosted in a wide variety of materials. Chip-integrated quantum transducers enable high Q cavities with ultrasmall mode volumes and provide enhanced coupling between carriers while maintaining their quantum correlations. Here the transduction materials play a central role as they must meet stringent requirements for simultaneously providing strong nonlinearity and very low carrier loss.

An important capability that could be created by NSF for the advancement of quantum transduction is the development of a visible light photonics foundry. Recent developments in silicon-based photonics have led to the rapid adoption of photonic chip technology in CMOS foundries. Most photonic systems and foundries focus on devices operating in telecommunication bands. However, quantum information processors involving atoms and ions are operated in the visible band. Atomic clocks, visible light communications, and photonic applications in biological and medical areas also benefit from visible photonic chips. Therefore, the development of visible light platforms based on wideband semiconductors (III-nitride for example, in the range 350 – 750 nm) will provide substantial leverage to many research and application areas.

7.3.5 Ultra-Wide Bandgap Materials

As discussed by Steve DenBaars and Grace Xing, AlGaN material system allows great flexibility in tuning UV light emission from LEDs and laser to wavelengths spanning 200 nm to 390 nm. UV-C LEDs emitting at 270 nm with powers as high as 7 mW and 5% external quantum efficiency (EQE) have been demonstrated. At these levels the LEDs already show great promise in sterilizing COVID-19 in air, water, and surface decontamination. However, the high Al composition in the LEDs leads to high dislocation densities (10^9 cm^{-2}) and strong piezoelectric effects which hinder the efficiency and performance. By incorporating other elements such as B and In in the AlGaN alloys, lattice-matched and strain and piezoelectric free structures could be achieved. Additionally, if bulk AlN substrates can be grown with low defect densities, UV lasers and high-power electronic devices can also be realized. The advent of bulk AlN crystals would also enable other crystal planes in semi-polar and non-polar orientations to be incorporated into active devices. These materials improvements would be key developments in realizing UV photonic devices with greater than 60% EQE and high-power operation. To fully unleash the potential of these materials, it is critical to: 1) control defect levels below the limits that the targeted applications can tolerate, 2) control doping for both n-type and p-type regions, and 3) engineer the most effective carrier injection into the conduction and valence bands. Deep-UV emitters present formidable challenges for meeting these requirements simultaneously.

7.3.6 Narrow Bandgap Materials

In the last 15 years, the spectral range for high-performance III-V semiconductor lasers and detectors has expanded into the midwave and longwave infrared. This was explained in presentations by Manijeh Razeghi and Jerry Meyer. With continued investment by NSF and other government agencies, the next 15 years will witness a dramatic transformation of these macroscopic devices, which now require bulky external optics, into building-block components for portable optoelectronic systems residing on a single chip. Photonic integrated circuits (PICs), processed on silicon or the native InP and GaSb substrates, could combine multiple lasers and detectors with other active and passive elements, and possibly incorporate metamaterial enhancements, to provide functionalities that currently require a benchtop implementation. Inexpensive and ultra-compact chemical sensing PICs, operating with battery or solar power, could be deployed on smartphones and other portable platforms to provide biosensing, breath analysis, greenhouse gas monitoring, and industrial process control, as well as detection of leaks, hazardous gases and explosives. Dual-frequency-comb spectroscopy could provide simultaneous broadband detection of multiple chemical species, rapidly enough to probe molecular dynamics in real time. Wavelength-tunable, narrow-band detectors incorporating vertical and in-plane resonant cavities could provide hyperspectral detection and imaging with enhanced sensitivity.

7.4 Session 4 Findings – Advancing Organic/Biodevices: Sensing, Stimulation, & Communication

Semiconductor research has largely focused on the design, synthesis, and fabrication of traditional, or hard, platforms in order to realize new and more complex functions. During the last couple of decades, however, the advancement of soft materials, such as organic semiconductors and the utilization and integration of heterogenous hard/soft materials platforms has advanced rapidly. Experts in Session 4 articulated the current status and key research challenges in continuing to advance organic semiconductors for low-cost electronic and optoelectronic applications to integrated platforms for advanced biological sensing, discovery, and physiological modification, such as drug delivery and modulation of biological function. Despite tremendous advances, key challenges remain and are outlined below. These challenges range from materials design and synthesis to optimizing specific properties, to the integration of materials to achieve specific functions bounded by use-specific environmental constraints, to the advancement of “traditional” hardware that can be integrated into systems tailored to specific sensing, delivery, and stimulation needs.

7.4.1 Grand Challenge – Biocompatible Materials and Abiotic/Biotic Interfaces

Currently, we have only a rudimentary understanding of the fundamental chemical and electronic properties that underlie materials biocompatibility. To date, the primary approach to assessing biocompatibility is largely empirical. The toxicity of materials components also requires further consideration. Experimental and theoretical research that elucidates the environment-dependent interactions of biological materials with engineered materials is needed to advance electronic and optoelectronic systems for a range of biomedical applications.

7.4.2 Heterogeneous Integration of Hard and Soft Materials

The challenges associated with integrating dissimilar materials are particularly important to realizing body-integratable systems. In addition to the fundamental challenges of 3D materials and device integration, biosystem compatibility introduces constraints associated with mechanical properties, such as flexibility and geometry. Impedance matching is always important but more complex in systems harnessing both electronic and ionic conduction. Finally, a key challenge is the integration of biocompatible systems with advanced electronics.

7.4.3 Advances in Organic Semiconductors

Organic semiconductors are particularly important for low-cost, large area manufacturing, and flexible device applications and, as discussed by Steve Forrest, have seen tremendous advances in the past three decades. The organic light-emitting diode (OLED) display is now part of a $30B industry. Organic solar cells have demonstrated 10% efficiency with 50% transparency[34]. Given the enormous variability of materials properties through chemical synthesis, combined with the ability to deposit organic thin films on almost any smooth, ultra-large area, flexible and lightweight substrate, organic electronics provide an opportunity to serve new application spaces that are inaccessible to conventional electronics.

Unfortunately, the U.S. has let manufacturing of large organic electronic appliances go to Asia, although a considerable proportion of new intellectual property is still being generated in domestic laboratories. The off-shoring of manufacturing, however, has also made our lead in intellectual property development tenuous at best. To continue and strengthen U.S. innovation, with the ultimate goal of manufacturing next generation organic electronic devices in America, NSF should continue to invest in organic semiconductors with focus on a number of factors. (1) Methods to improve material purity. Purification today is typically done by sorting materials by molecular weight. Directed programs are needed to synthesize and characterize high purity materials to enable revolutionary advances. (2) High energy light emitters – blue OLEDs have been demonstrated, but the emitted photons are of sufficient energy to break bonds, therefore leading to materials and device degradation. This problem needs further investigation. Electrically-pumped organic lasers are yet to be realized. (3) Processing, manufacturing, and metrology need continuous investment around well-defined organic device application targets to bring manufacturing to the U.S. in new application spaces. (4) Developing applications in current optoelectronic "white spaces" such as in conformable medical sensors, gas sensors, etc. (6) Exploiting the unique spin-stable and quantum dot nature of molecular species in optical cavities and other architectures as a means to control chemical reactions, spin transport for quantum information processing, artificial photosynthesis, etc.

7.4.4 Extension of Photonic Emitter and Detector Wavelengths (UV to IR)

Imaging is crucial to discovery and sensing in biomedical applications. Numerous imaging modalities have been demonstrated in the last decade. A key challenge is the ability to build systems that integrate multiple imaging modalities in a compact system. Here, the advancement of light emitters and detectors over a broad range of wavelengths is crucial.

7.4.5 Engineering Regeneration for Health

Electronic devices that enhance physiological function, such as cochlear implants, have been developed for decades. However, we are at the cusp of being able to utilize advanced devices based on this early model that simultaneously sense and modulate biological function. From drug delivery to neurological pathway modulation, these platforms must build upon the challenges discussed earlier; body-integratable devices with appropriate form factors and flexibility, biocompatability, and the ability to trigger function or device degradation on-command.

8. Discussion

The workshop highlighted recent innovations in semiconductor materials that can have profound benefits for future devices and circuits. A general consensus is that the field of semiconductors is more vibrant today than ever before, with a future that promises ever more applications for computation, memory, communication, imaging, and sensing. Participants described discovery of the richness of electronic phases in semiconductors, allowing ferroelectric, ferromagnetic or even superconducting behavior. Topological materials hold the promise of more robust electron transport, even in the presence of defects. Vacancies in semiconductor materials have been shown to exhibit robust spin and photon behavior. Better known materials, such as GaN continue to promise as-yet untapped potential for new electronic and photonic device and systems performance. Organic semiconductors, polymers and biogenic materials promise new advances in medical monitoring, diagnoses, and treatments. Thus, rather than a field in which all major challenges have been addressed, and all possible applications have been explored, there are major new opportunities for semiconductors. The plethora of scientific advances happening today in semiconductor science and technology is destined to create entirely new industries and new kinds of semiconductor foundries in the near future. The strongest technological growth areas in the next decade are: 1) merging logic with memory devices, 2) quantum computation & communications, 3) mm-wave RF electronics, 4) deep-UV photonics, 5) power electronics, and 6) biophotonics. Key fundamental challenges, while addressed for decades, remain unanswered and important, such as surface passivation and control and biocompatibility. New semiconductor materials, devices, and circuits and systems are being developed for these up and coming industries. Countries that invest now will reap the economic and scientific benefits for decades to come in each of these categories, which must receive balanced attention and investment.

However, as workshop participants emphasized, there is a large gap between the discovery and characterization of new materials and their implementation within new device and circuit technologies. Moreover, although the U.S. enjoys leadership on several research fronts, it is increasingly falling behind globally because of an aging, inefficient and underserved semiconductor research infrastructure. Countries in Europe and Asia have recognized the strategic importance of semiconductors to their economic, societal, and technological well-beings, and as a result have committed substantial resources to develop research infrastructure and funding, and have also actively engaged their younger generation in making contributions to these areas. China, for example, is actively recruiting the return of U.S.-trained Chinese doctoral students through the Thousand Talents Plan[35].

The long-term future and health of semiconductor innovation, technological translation and industrial leadership is a complex challenge that will involve many organizations within the U.S. The NSF has a critical, strategic role to play in ensuring a robust future of semiconductors. Based on the presentations and discussions of the workshop, we make recommendations for investment in areas related to infrastructure, funding availability and accessibility, a continued focus on multi-disciplinary initiatives that are integrated both laterally *and* vertically, and supportive investments in education programs.

8.1 Supporting an Integrative Infrastructure Network in materials, design and computation, device fabrication, metrology, benchmarking, and reliability studies

A general conclusion presented by workshop participants, regardless of their particular material or device focus, was that the successful transfer of materials innovations into augmented device and circuit performance requires the following resources and focus areas:

1. Developing methods and tools for materials synthesis.

2. Developing the appropriate fabrication methods for new materials and device geometries.

3. Developing appropriate characterization and metrology for new materials and devices. Particular challenges may include techniques that have the appropriate spatial resolution (which may be atomic scale), yet also be able to address large areas, and done in rapid time scales.

4. Providing the close collaboration and exchange of materials and devices between materials experts, device experts, and circuit designers. The above challenges are not qualitatively different from those that academic researchers have faced in the past. However, the nature and complexity of the new materials, limited access to these materials and to the appropriate instrumentation for their characterization, and the processes for fabrication into devices, makes the necessary integrated advances much harder to achieve.

Furthermore, to guide the community of researchers in better translation of material innovation into new systems realization, the following factors should also be considered:

5. Appropriate metrology of materials and devices should be undertaken. The stereotyped academic researcher wishes to only report on a single "best device" or "best material performance". In fact, an academic researcher may not have sufficient materials, frequent-enough access to device fabrication, or access to appropriate characterization tools to carry the analysis that provides information on the robustness of a material or device. To encourage more effective “translational research”, the appropriate tools and training on techniques need to be available.

6. Understanding and developing methods and measurements for device reliability.

7. Appropriate benchmarking of material and device operation, on a recognized, easily obtained platform. Although there are some foundries available to provide CMOS platforms, including Taiwan Semiconductor Manufacturing Company (TSMC) and the Interuniversity Microelectronics Centre (Imec, Leuven, Belgium), and the recently created AIM-Photonics[36] for photonic circuits, these few services can be expensive, slow[37], and relatively constrained in materials and devices that will be allowed. In the past, there was a well-recognized and largely accepted differentiation between materials and device innovation appropriate to academia, and the scaled-up and far more complex processes for systems design and manufacture in industry. In many ways, the gaps of understanding and approaches have grown considerably larger in the past few decades. In addition, the socioeconomic demands on both industry and universities have dramatically changed in the past decades, that necessitate a reconsideration of the best of ways of collaboration. Industry has increasing competitive pressures to deliver manufacturable, reliable new technologies at low cost, while at the same time understanding the well-spring of new resources that can fuel future innovation. Universities need to pursue fundamental science and engineering research that have longer timelines for development, need to understand major societal challenges, and have the sustainable resources to address those challenges. The NSF can play an important role in helping to bridge these divergent requirements, if it engages in

this integrative rethinking of the needs and resources that industry, university and national labs collectively bring to the Future of Semiconductors.

8. New semiconductor and electronic materials meant to augment performance in integrated circuit technology need integration platforms on which to explore scaling and compatibility, and to demonstrate performance. In collaboration with universities, companies need a single point of contact if they are to provide this collaboration to multiple universities and small business ventures. A model for this is MOSIS (Metal Oxide Silicon Implementation System, https://www.themosisservice.com/) which allows university researchers to submit circuit designs to be fabricated in foundry processes at TSMC or GlobalFoundries in many technology nodes. What is needed is infrastructure which would enable universities to get ICs which are opened for processing in the back-end-of-line (BEOL). This intermediary service must include process design kits (pdks). Companies need to standardize alignment marks for university users to implement BEOL fabrication. There is value to students learning leading edge technology while also tackling the problems of new materials integration. The science and technological issues are usually deeply nested. There are needs for these materials translation platforms to manufacturing that go beyond integration with CMOS, including III-V and III-N integrated technology for RF and power applications. Programs of this type need a centralized infrastructure and the development of cost models for funding including multiple stakeholders in industry and government.

Points 1- 8 indicate infrastructure needs to provide the research community with augmented, and in some cases *new* instrumentation, resource, and benchmarking capabilities. The NSF has provided sustained leadership in infrastructure support in materials and fabrication, through the Materials Research Science and Engineering Centers (MRSECs), Science and Technology Centers (STCs), Engineering Research Centers (ERCs), and the National Nanotechnology Coordinated Infrastructure (NNCI). These have provided opportunities for the broad community of U.S. researchers to access a wider range of capabilities and the accompanying expertise than single investigators or particular universities could support.

Continuing investments in infrastructure are needed to support *infrastructure capabilities* that:

- Provide sufficient staff to allow training, advising and provision of materials or devices samples and their analyses.
- Operate in a sustained fashion and are not faced with curtailment after a 5-year period, for example. The NSF should not promise to fund initiatives indefinitely. However, such user facilities are critically important for the research community, and some new deliberations on sustainable business models should be undertaken.
- Focus on benchmarking and metrology of materials, devices, and circuits. Benchmarking has at least two connotations: (1) availability of foundry-like services to provide integration with, and benchmarking of performance of new devices on an established (CMOS) platform. This capability would benefit from collaborative discussions between industry, the NSF and other government organizations. (2) Benchmarking also requires capabilities for evaluating device performance in a well-calibrated way, similar to the way that the National Renewable Energy Laboratory (NREL) does for solar cells. This might represent an opportunity for new NSF-funded facilities which emphasize metrology.

8.2 Revising/Augmenting the Support Model for “Translational” Semiconductor Innovation

The typical size of individual investigator grants from the NSF today are incompatible with research in semiconductors. For many new researchers, the NSF provides the sole source of support. A grant size that cannot pay for the use of semiconductor synthesis or fabrication is a non-starter. We understand the economic constraints on the NSF, as well as the aim to make funding available to as large a group of talented innovators as possible. Yet a focus on materials, device and circuit innovation that can truly be translated into technological leadership in the commercial sphere requires the commensurate funding to allow that fuller research to take place, to not only set up infrastructure facilities, but also to ensure that researchers can put together proposals where the costs of materials synthesis, characterization, and device development can be properly resourced. It is important to attract the best and brightest young people to materials and hardware development and projects need to aim big to attract them.

The NSF should allocate resources to fix this supply problem by accepting larger budgets and more multi-principal-investigator projects, plus-ups, and equipment support to early Career award winners that perform experimental work in semiconductors. Support of exciting research in this area, together with funded programs focused on this area, such as the NSF Research Training (NRT) program, could attract more students to these fields at the Ph.D. level. This increase is needed for entrepreneurs that dream of converting their discoveries into products, to ensure that the technology developed is made in U.S. As an example, a multidisciplinary team including materials growth, characterization (including new metrology or analytical methods), plus fabrication and analysis could cost $1.2-1.5M for a 3-year effort. This is a level needed to tackle more complex problems.

8.3 Lowering Barriers to Multi-disciplinary, Convergent Programs

The Workshop entertained a variety of discussions across widely diverse fields of knowledge; there is clear need to further build bridges across disciplines. Although the discussions in Session 4 highlighted the challenges in integrating biomedical, chemical, and physical expertise, all sessions pointed out the need to engage in horizontally and vertically integrated research environments.

Through center-based endeavors, like the ERCs, the NSF has been an effective catalyst in this regard. However, the “cost of entry" is considerable, to center-type activities like ERCs, STCs and MRSECs, although the benefits may be long lasting. We suggest that the NSF developing more convergent center programs, along the lines of the Emerging Frontiers in Research and Innovation (EFRI) programs. These should be funded for 3 - 5-year time frames, bringing together different disciplinary areas focused on an important societal grand challenge. Analogous programs in Emerging Frontiers in Education Innovation might also be considered. The intention should be to lower the barrier to entry vs. ERCs, STCs, and MRSECs and more quickly facilitate the sharing and implementation of ideas among convergent teams.

8.4 Re-stocking the Pipeline for Next-Generation Innovators in Semiconductors

The presentations and discussions of the Workshop revealed the broad range of materials performance and applications spanned by semiconductor materials. It is important to convey this wealth of possibilities to the bright young researchers and innovators of the future, and to also provide them with the tools, research opportunities and inspirational and foundational education that will allow them to create the new semiconductor industries of the future. Young entrepreneurs in these fields have faced an asymmetric challenge in opportunities and funding, compared to colleagues focused on software innovation, because of the high costs of capital investment in equipment and infrastructure. The NSF could help to “re-stock” this pipeline, through making infrastructure tools more widely accessible for research in this area, for creating NRTs and other education programs in convergent research areas involving semiconductor research.

8.5 New Areas for NSF Investment

8.5.1 Millimeter-wave Grand Challenge

Millimeter-wave (mmW, 30 GHz to 300 GHz) technologies are becoming increasingly important for systems requiring high directional control and bandwidth, including 5G communications, automotive/ navigational radar sensors, and point-to-point links. Although 5G networks make use of both mmW and lower frequency RF technologies, use cases that require very high bandwidth continue to be identified driving increasing needs for mmW frequency systems. Furthermore, there are significant advantages to the directional and bounded propagation characteristics of mmW signals, for both private and enterprise applications, including sensors and secure networks.

Although advances in mature semiconductor technologies, such as Si, SiGe, GaAs, InP, and GaN have enabled incredible performance from mmW circuits and subsystems (including phased arrays) below 100 GHz, there remain significant challenges that could be addressed by revolutionary advances in new electronic materials. Present electronic component gaps for mmW systems include tunable filters, transducers, and non-volatile switches, largely because materials are not yet available to support operation of these components at mmW frequencies. Furthermore, the bandwidth advantages of systems built above 100 GHz are currently inaccessible due to active component limitations, even in relatively mature semiconductor technologies, such as GaN.

Specific opportunities for NSF to enable US competitiveness in future mmW systems include:

- Advances in wide bandgap materials and devices to push the frontier for operation of high power, high efficiency, active circuits to the 100-300 GHz range

- Lightweight ferroic materials that are compatible with semiconductor wafer fabrication for tunable filtering throughout the mmW band

- Materials for efficient transduction of optical and mechanical energy to millimeter-wave frequencies (see Session 3 summary)

- Phase change materials for non-volatile, high performance switching in the 100-300 GHz range

8.5.2 Semiconductors for the Nation`s Infrastructure

As the events of the past year have dramatized, U.S. infrastructure (roads, tunnels, bridges, water supply systems) is largely aging, rapidly deteriorating, and therefore poses threats to continued health and safety. Although infrastructure is not one of the NSF`s 10 Big Ideas, this area has particular relevance as the country makes decisions about returning to conventional workspaces and urban environments. Semiconductors, current and future, play a critical role in the devices that enable the Internet of Things, and could play an important role in the reconstruction of a smart and sustainable infrastructure. China has made much of its Belt and Road initiative.[38] Perhaps the NSF could play a role in an analogous U.S initiative.

9. Summary Program Recommendations

The following are high-priority program recommendations for NSF in semiconductors. In these programs the NSF can be most impactful by focusing on materials science and engineering, including materials synthesis, defect characterization and control, metrology for probing critical and often buried device heterojunctions, and fundamentals studies necessary to develop predictive and experimentally validated material/device models. Detailed understanding and control of materials is critical to go from one-of demonstrations to reliable and manufacturable future technologies.

9.1 Harnessing electronic phases and phase transitions

A wide range of new devices can be expected to emerge in the development of semiconducting materials which harness phase transitions. Devices operating about these phase-critical points can bring new functionality and break traditional device limits. Research is needed in the following areas. (1) Identify and synthesize ferroelectric semiconductor materials. (2) Identify new semiconductor device functions that are enabled by ferroelectric semiconductors or by integration of ferroelectrics with semiconductors. (3) Identify and expand the set of semiconductors that exhibit superconducting behavior. (4) Identify new device functionalities that exploit reversible phase transitions between semiconducting and superconducting phases. (5) Explore the science of semiconductor/superconductor interfaces and the transport of charge, spin, and phase across them. (6) Identify new device functionalities enabled by new forms of semiconductor/superconductor junctions. (7) Identify and synthesize semiconductors that exhibit room-temperature ferromagnetism. (8) Identify device applications enabled by magnetic semiconductors or close integration of spin-torque or spin-orbit torque with semiconductors. (9) Identify semiconductors that exhibit ultrafast structural phase transitions that influence their electronic properties. (10) Identify new device functionalities that exploit the change of electronic properties resulting from ultrafast structural phase changes.

9.2 Ultra-wide-bandgap semiconductors

Ultra-wide bandgap semiconductors, such as the III-Nitrides, gallium oxide, and diamond, have wide ranging applications in power conversion and power grid control systems. The wide bandgap enables high temperature operation and a radiation resistance which opens up applications in harsh environments. The wide bandgap also opens up capabilities for light emitting diodes. By incorporating other elements such as B and In in AlGaN alloys, lattice-matched and strain and piezoelectric free structures can be achieved. Additionally, if bulk AlN substrates can be grown with low defect densities, UV lasers and higher-power electronic devices can also be realized. The advent of bulk AlN crystals would also enable other crystal planes in semi-polar and non-polar orientations to be incorporated into active devices. Ultra-wide-bandgap semiconductor programs are recommended that are motivated by applications, and do so by a focus on solution of materials problems. For example, materials improvements would be key developments in realizing UV photonic devices with greater than 60% EQE and high-power operation. To fully unleash the potential of these materials, it is critical to: 1) control defect levels below the limits that the targeted applications can tolerate, 2) control doping for both n-type and p-type regions, and 3) engineer the most effective carrier injection into the conduction and valence bands. Deep-UV emitters present formidable challenges for simultaneously meeting these requirements. Imaging is crucial to discovery and sensing in biomedical applications. Numerous imaging modalities have been demonstrated in the last decade. A key challenge is the ability to build systems that integrate multiple imaging modalities in a compact system. Here, the advancement of light emitters and detectors over a broad range of wavelengths is crucial. The wider availability of high quality AlN materials, whether as substrates or thin films, would also be important for realization of mechanical actuators, acoustic tuning of strain, with possible applications for emerging quantum information technologies.

9.3 Millimeter-wave materials and devices

Millimeter-wave (mmW, 30 GHz to 300 GHz) technologies are becoming increasingly important for systems requiring high directional control and bandwidth, including 5G communications, automotive/ navigational radar sensors, and point-to-point links. Although 5G networks make use of both mmW and lower frequency RF technologies, use cases that require very high bandwidth continue to be identified driving increasing needs for mmW frequency systems. Furthermore, there are significant advantages to the directional and bounded propagation characteristics of mmW signals, for both private and enterprise applications, including sensors and secure networks. Although advances in mature semiconductor technologies, such as Si, SiGe, GaAs, InP, and GaN have enabled incredible performance from mmW circuits and subsystems (including phased arrays) below 100 GHz, there remain significant challenges that could be addressed by revolutionary advances in new electronic materials. Present electronic component gaps for mmW systems include tunable filters, transducers, and non-volatile switches, largely because materials are not yet available to support operation of these components at mmW frequencies. Furthermore, the bandwidth advantages of systems built above 100 GHz are currently inaccessible due to active component limitations, even in relatively mature semiconductor technologies, such as GaN. Specific target opportunities to enable US competitiveness in future mmW systems include (1) extend frontiers in wide bandgap materials and devices for operation of high power, high efficiency, active circuits to the 100-300 GHz range, (2) Realize lightweight ferroic materials that are compatible with semiconductor wafer fabrication for tunable filtering throughout the mmW band, (3) Realize materials for efficient transduction of optical and mechanical energy to millimeter-wave frequencies for filters, and (4) Develop phase change materials for non-volatile, high performance switching in the 100-300 GHz range

9.4 Infrared photonic materials and devices

The spectral range for high-performance III-V semiconductor lasers and detectors has expanded into the midwave (3-5 μm) and longwave (8-12 μm) infrared. There is need for dramatic transformation of these macroscopic devices, which now require bulky external optics, into building-block components for portable optoelectronic systems residing on a single chip. Infrared photonic integrated circuits (IPICs), processed on InP and GaSb substrates, could combine multiple lasers and detectors with other active and passive elements to provide functionalities that currently require a benchtop implementation. Significant challenges must be met to enable IPICs, including low-loss waveguide-based gain and modulation elements, metamaterial enhancements for wavelength selection, and integration methods for relatively fragile elements and host substrates. Inexpensive and ultra-compact chemical sensing IPICs, operating with battery or solar power, could be deployed on smartphones and other portable platforms to provide biosensing, breath analysis, greenhouse gas monitoring, and industrial process control, as well as detection of leaks, hazardous gases, and explosives. Dual-frequency-comb spectroscopy could provide simultaneous broadband detection of multiple chemical species, rapidly enough to probe molecular dynamics in real time. Wavelength-tunable, narrow-band detectors incorporating vertical and in-plane resonant cavities could provide hyperspectral detection and imaging with enhanced sensitivity.

9.5 Visible spectrum sources for quantum transduction and networking

To enable multibit quantum computing and quantum communication systems, photonic technologies are needed for quantum state modality transduction and quantum information transmission through photonic networks. Quantum systems rely on faithful quantum state transfer between disparate modalities, implemented in a variety of two-level qubits. Chip-integrated quantum transducers are needed to transform quantum information for detection and transmission while maintaining their quantum correlations. The transduction materials must simultaneously provide strong nonlinearity at low carrier loss. Photonic systems and foundries today are based on devices operating in the telecommunication bands. However, quantum information processors involving atoms and ions are operated in the visible band. New integrated on-chip and off-chip systems to transform quantum information to photonic systems wavelengths for small-scale (within the system) transfer of information to large-scale (between quantum information transmitters and receivers) is needed.

9.6 Organic semiconductors

To strengthen U.S. innovation, with the ultimate goal of manufacturing next generation organic electronic devices in America, research is needed in the following areas. (1) Methods to improve material purity. Purification today is typically done by sorting materials by molecular weight. Directed programs are needed to synthesize and characterize high purity materials to enable revolutionary advances. (2) High energy light emitters – blue OLEDs have been demonstrated, but the emitted photons are of sufficient energy to break bonds, therefore leading to materials and device degradation. This problem needs further investigation. Electrically-pumped organic lasers are yet to be realized. (3) Processing, manufacturing, and metrology need continuous investment around well-defined organic device application targets to bring manufacturing to the U.S. in new application spaces. (4) Developing applications in current optoelectronic “white spaces” such as in conformable medical sensors, gas sensors, etc. (5) Exploiting the unique spin-stable and quantum dot nature of molecular species in optical cavities and other architectures as a means to control chemical reactions, spin transport for quantum information processing, artificial photosynthesis, etc.

9.7 Electronic and photonic interfaces to biological systems

Electronic devices that enhance physiological function, such as cochlear implants, have been developed for decades. However, it is now possible to utilize advanced devices based on this early model that can both sense and modulate biological function. From drug delivery to neurological pathway modulation, integrated platforms that can be utilized in biological systems, while being conformable and biocompatible, are sorely needed. This challenge involves the ability to design and control abiotic/biotic interfaces. Materials biocompatibility remains poorly understood. The fundamental chemical/electronic coupling at the interfaces and surfaces of soft/hard materials, e.g. biological/semiconductor systems, must be better understood as they provide the foundation for future functional, integrated systems. With such an understanding, devices from drug delivery to sensing can be used to gain new functionality, from triggering physiological responses for regenerative treatments, to unraveling the communication pathways in living organizations. New devices compatible with ex situ physiological modulation, such as photonic devices compatible with sensing and modulating individual cell in cellular network function are needed.

9.8 Level of funding

For each of these programs, it is recommended that a wide variety of funding levels be allowed. For new faculty, who are often encouraged to distinguish themselves in single-investigator programs, the single investigator option should be available. However, there can be significant acceleration of progress by funding multidisciplinary teams. Sizes of these programs should be flexible, from 2 to 3 investigators all the way to larger teams (e.g. 8 – 10 PIs). Investigators can best scope out team sizes to successfully execute their goals.

10. Concluding Remarks

It has taken 60 years for scientists and engineers working on silicon to solve the materials issues needed to yield the robust and ubiquitous electronics technology of today. It should not be expected that new materials and devices can come to this level of maturity in a three-year program. Sometimes programs appear to have this expectation. As promising materials are incorporated into new devices, it is all-too common that following the initial demonstration, the concept is left to industry to carry forward, well before the challenges relating to reproducibility, reliability, and defect mitigation, are solved. In part, there is a belief that such research and engineering, required to bring a new material concept into application reality, is the role of industry, not academia. This is reinforced by a funding infrastructure that places the necessary tools and expertise out of economic reach of the researchers. Methods to sustain promising programs should be developed to move initial demonstrations into fundamental studies that are needed to understand and control defects and ultimately to effectively prepare the technology for manufacturing. Some of the challenges are in metrology. Device engineers need better methods to characterize the physical and electrical properties of buried interfaces. For many emerging research areas, long runways (5 years and longer) and collaborations with industry are needed to solve these problems, especially when the research involves teams that cross disciplines, e.g. electronics, organic materials, and biology.

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