

COMMITTEE ON TECHNOLOGY
SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

National Nanotechnology Initiative Signature Initiative:

Nanoelectronics for 2020 and Beyond

July 2010 Final Draft

Collaborating Agencies¹: NSF, DOD, NIST, DOE, IC

National Need Addressed

The semiconductor industry is a major driver of the modern economy and has accounted for a large proportion of the productivity gains that have characterized the global economy since the 1990s. One indication of this industry's economic importance is that in 2008 it was the second largest exporter of goods in the United States. Recent advances in this area have been fueled by what is known as Moore's Law scaling, which has successfully predicted the exponential increase in the performance of computing devices for the last 40 years. This gain has been achieved due to ever-increasing miniaturization of semiconductor processing and memory devices (smaller and faster switches or transistors). However, because the physical length scales of these devices are now reaching atomic dimensions, it is widely believed that further progress will be stalled by limits imposed by the fundamental physics of devices [ITRS, 2005].

Continuing to shrink device dimensions is important in order to further increase processing speed, reduce device switching energy, increase system functionality, and reduce manufacturing cost per bit. But as the dimensions of critical elements of devices approach atomic size, quantum tunneling and other quantum effects degrade and ultimately prohibit conventional device operation. Researchers are therefore pursuing somewhat radical approaches to overcome these fundamental physics limitations. Candidate approaches include different types of logic using cellular automata or quantum entanglement and superposition; 3-D spatial architectures; and information-carrying variables other than electron charge such as photon polarization, electron spin, and position and states of atoms and molecules. Approaches based on nanoscale science, engineering, and technology are the most promising for realizing these radical changes and are expected to change the very nature of electronics and the essence of how electronics are manufactured. Rapidly reinforcing domestic R&D successes in these arenas could establish a U.S. domestic manufacturing base that will dominate 21st century electronics commerce.

This multi-agency R&D initiative is aimed at discovering and using novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of nanoelectronics. The initiative has five thrust areas:

- Exploring new or alternative "state variables" for computing
- Merging nanophotonics with nanoelectronics
- Exploring carbon-based nanoelectronics
- Exploiting nanoscale processes and phenomena for quantum information science

¹ Please note that "collaborating agencies" is meant in the broadest sense and does not necessarily imply that agencies provide additional funds or incur obligation to do so. Agencies leading this effort and responsible for proposed initiatives are underlined.

- National Nanoelectronics Research and Manufacturing Infrastructure Network (university-based infrastructure)

Technical Program

Brief descriptions of each proposed thrust area are presented in the following.

Thrust 1: Exploring new or alternative “state variables,” architectures, and modes of operation for computing

Alternative “state variables,” other than charge transfer exploited by conventional transistors, have been envisioned. These alternatives include electron spin devices, magnetic devices, quantum cellular automata, and computations on biological substrates. At the nanoscale it is not only the devices themselves but interconnecting them to build a functional architecture that poses formidable problems. Many nanoscale interconnection devices have been recently explored (from carbon nanotubes to on-chip optical interconnects, plasmonic devices, etc.), but the device architecture, interconnection problems, fabrication/assembly methods, and complex behavior of large nanosystems remain largely unresolved. Because atomic and nanoscale phenomena introduce many uncertainties in the devices themselves, from the viewpoint of both fundamental physics and manufacturing imperfections it is also a formidable challenge to conceive of architectures that will provide robust systems out of unreliable nanoscale components. Many alternative solutions to this problem have been proposed; one interesting possibility is to exploit biologically inspired, guided self-assembly to produce reliable nanoscale components. This may in turn lead to the development of “green” electronics manufacturing processes.

Expected Outcomes

- Nano-electro-mechanical carbon-based “switch” representing a state variable instead of 6 to 12 CMOS transistors
- Understanding of the role of the memresistor for future device design and architecture implementation
- Specially designed and characterized test structures that validate emerging nanoelectronic components and devices through measurement of key parameters.
- The development of innovative measurements to enable highly energy efficient transistors and memory.
- Demonstration of new measurements that allow integration of beyond-CMOS technologies into microelectronic products offered by US companies.

Thrust 2: Merging nanophotonics with nanoelectronics

Photonics has potential for a wide range of applications beyond the optical communications arena and computation. More specifically, silicon photonics (or silicon-based optoelectronics) together with the CMOS platform is beginning to become a technical focus, because it potentially offers an entirely new generation of low-cost photonic integrated circuits that will perform functions traditionally accomplished using much more expensive components based on III-V semiconductor materials. The primary driving force for silicon photonics development is the demand for cost-effective optical interconnect technology in the microelectronics industry. As a subset to this area, plasmonics has emerged as an exciting new field of science and technology that aims to exploit the unique optical properties of metallic nanostructures to enable routing and manipulation of light at the nanoscale. Nanometallic objects derive their astounding properties from their ability to support collective electron excitations, known as surface plasmons. Presently there is explosive growth in both the number and range of plasmonics applications; it is

becoming eminently clear that both new fundamental science and new device technologies are being enabled by the current plasmonics revolution.

As plasmonics technology has enabled optics to catch up with electronics in the race for miniaturization, new opportunities are emerging at the interface between these technologies. Hybrid nanophotonic devices containing both nanoscale metallic and semiconductor components can provide new functionalities that cannot be attained with either technology by itself. Whereas metals offer unparalleled light concentration, semiconductors offer advanced electronic functions in addition to valuable light emission, detection, and a wide variety of nonlinear optical properties. By taking advantage of the best aspects of both technologies, new devices allowing for simultaneous electronic and optical functions can be realized. Such devices include new light sources, detectors, sensors, frequency converters, modulators, quantum optical, and ultrafast optical components. Topics of interest within this thrust area include, but are not limited to, the following: (1) novel material processing and fabrication techniques for realizing hybrid semiconducting/metallic materials and nanostructures, (2) CMOS-compatible fabrication routes towards the development of hybrid nanophotonic systems, (3) nanoscale plasmonic sources and detectors, (4) plasmonic cavities doped with semiconductor gain materials for optical amplification or lasing, (5) plasmonics structures that incorporate nonlinear materials for ultracompact optical modulators or frequency converters, (6) doped nanoscale optical antennas for directed and smart sources, and (7) novel computational and analytic design strategies for hybrid nanophotonics devices.

The overarching objectives for this thrust area are for the United States to remain a leader in silicon photonics integration and for silicon photonics to become a major emerging system enabler. This will be enabled in part through remarkable advances in silicon nanophotonics. This in turn will enable convergence of computing & optical communication.

Expected Outcomes

- Enhanced photonic device performance through integrated optical interconnects
- Unified modeling of photonics, plasmonics and electronics components under circuit equation solver like SPICE to seek newer applications on the hybrid substrate.
- 3D optical interconnects & 3D optical chip functions
- A domestic base to fabricate chip-scale photonic devices and networks using the CMOS processing line and base
- Tool bag of active and passive plasmonic devices and functions
- Near term: multiple plasmonic source, detector, antenna, modulator options
- Understanding the role of plasmonics in optical interconnect technology
- Development of tools/techniques for analysis of photonic-crystal-chips, plasmonics and related issues: numerical techniques, use of parallel/distributed computing, framework for optimization and scanning (E&M solvers, FDTD approaches, merging E&M and Quantum).
- Comprehensive design and experimental realization of subwavelength active and passive devices
- Small circuit-like plasmonic networks.
- Delivery of ultracompact, robust and highly efficient photonic components and networks optimally suited for insertion into mobile small platforms.
- Photonic network on chip provide enormous capacity at dramatically low power consumption required for future multicore processors, both on- and off-chip
- Performance-per-Watt gains on communications-intensive applications

Thrust 3: *Exploring carbon-based nanoelectronics*

Carbon nanomaterials, carbon nanotubes, and more recently graphene, are characterized by many highly desirable electronic properties, among them ultrahigh mobility, possibility of innovative approaches to bandgap engineering, and ballistic transport at room temperature. In addition, these materials possess excellent thermoelectric properties, mechanical strength, and electromechanical properties. The thrust area on carbon-based nanoelectronics focuses on, among others: (1) continued efforts toward understanding the fundamental science responsible for the unusual physical behavior in these materials, (2) improved materials quality in areas such as large-area graphene synthesis, low-cost and high-throughput carbon nanotube sorting, and materials challenges associated with integrating carbon with CMOS technology, (3) exploration of innovative device constructs that go beyond the constraints of field effect transistors by utilizing the unique properties of graphene and carbon nanotubes, and (4) exploring novel functionalities in carbon nanomaterials that encompass electrical, optical, magnetic, thermal, and mechanical domains.

One area of particular interest within this thrust area is graphene. Graphene has caught the imagination of scientists and engineers across the globe. Many of its unusual physical properties, emanating from the fact that the charge carriers in graphene effectively behave like massless Dirac fermions, have now been successively predicted and confirmed experimentally. On the materials synthesis and applications side, progress is equally breathtaking. To date graphene has broken the records at room temperature for electrical mobility, mechanical strength, and thermal conductivity; graphene also exhibits remarkable chemical versatility. In 5 short years, graphene sample size has progressed from tiny flakes measuring a few dozen micrometers on the side produced using tedious labor-intensive mechanical exfoliation method, to tens of inches of monolayer graphene using CVD (chemical vapor deposition) growth on metal substrates. A graphene-based transistor with cutoff frequency up to 100GHz has been demonstrated. The peculiar physical, chemical and mechanical properties of graphene, some yet to be explored and hitherto undiscovered, may enable entirely new applications in areas such as carbon-based nano-electro-mechanical systems (NEMS), graphene-based spintronics as well as ultra-sensitive chemical and biological sensors – all related to nanoelectronics.

The overarching objectives for this thrust area are the development/maintenance of at least a five-year U.S. lead over other nations in electronics manufacturing, U.S. dominance in ultralow-power memory manufacturing, and the creation of domestic 21st century jobs. This will entail the development of a domestic carbon-based nanoelectronics manufacturing base from which to exploit other successes from the Nanoelectronics Research Initiative and a university-based research network. Success under this thrust area will ultimately lead to carbon-based electronics solutions to enable reduced power consumption and reduced heat production in smart appliances, consumer electronics, computers, servers, and data farms.

Expected Outcomes

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- Modeling and predictive analysis tools for the integration of carbon-based electronics with standard CMOS processes and the subsequent establishment of a carbon-based semiconductor industry
- Near-term (by 2011): demonstration of carbon-based logic circuits performing NAND, NOR, and NOT functions; manufacturing of low-power non-volatile 4M-bit carbon-based memories with equivalent switching performance as SRAMs
- Mid-term (by 2013): progressively more dense carbon-based memories (through 2-gigabit) with ultra-low power consumption and non-volatility that serve as a universal memory; initial demonstration of processors using carbon-based logic elements (memory management, data instruction cache, and L2 cache)

- Far-term (2015): carbon-based memories supplant CMOS memories (dual-in-line memory modules) in servers and data farms saving 60% of the power and reducing heat production by over 50%
- In the near term (~5 years), highly conductive transparent electrodes based on graphene will be developed.
- In the longer term (beyond 5 years), with the advancement of various techniques to fashion and control the electronic bandgap in graphene, graphene based active devices that enable entirely carbon-based nanoelectronic chips will be developed.

Thrust 4: *Exploiting nanoscale processes and phenomena for quantum information systems*²

Understanding and controlling quantum mechanical effects in nanoscale devices not only improves the performance envelope of conventional circuits—it changes the foundations of information technology. Key applications of quantum devices include secure communication, efficient solution of computationally hard problems, and new approaches for simulating systems in physics, chemistry, and life sciences. A quantum computer takes advantage of fundamental physical properties—quantum entanglement and superposition—that have no classical analog. For example, entanglement offers communication whose security depends only on the rules of quantum mechanics once detectors and sources are sufficiently sensitive and reliable. More involved implementations include Shor’s algorithm, which would render current information security used for e-commerce, banking, and defense ineffective and obsolete. The goal is to engineer devices where quantum phenomena—especially entanglement and superposition—can be reliably controlled, and to study how these influence nano- and microscale processes. This requires technological breakthroughs in nanoelectronics and device physics to achieve the control of individual electrons or nuclei in atoms, quantum dots, or other nanostructures.

This thrust’s special focus will be on (1) gaining control of the quantum state of nanoscale features and devices at the atomic level of precision; (2) understanding the impact and building the capability to simulate quantum phenomena in the nanoscale regime; (3) connecting quantum and nanoscale phenomena predictively across macroscopic length scales and time scales; (4) understanding and controlling decoherence in solid-state quantum systems on the nanoscale; and (5) creating hybrid quantum systems that connect nanoscale quantum systems with other quantum systems, whether they be atoms, photons, or other nanostructures. These activities require the development of novel fabrication, processing, and instrumentation techniques, and new theoretical and modeling tools.

Expected Outcomes

- Deliver a new, field usable, ultra-stable, optical atomic clock accurate to a few parts in 10^{17} based on a quantum information based protocol used to read out the clock state of an aluminum ion by interrogating the magnesium atom confined in the same trap
- Create a quantum network inside photonic crystals (PCs) made of quantum dots (QDs) in nanocavities
- Develop understanding of the role of diamond materials and nanostructures for quantum information systems
- Demonstrate long coherence time in spin qubits in Si-based quantum dots.

² See [NSTC, 2009].

**Thrust 5: National Nanoelectronics Research and Manufacturing Infrastructure Network:
University-based infrastructure**

Currently, U.S. academic facilities for nanoelectronics research are at a competitive disadvantage relative to the large instrumentation investments that have been and continue to be made in other developed countries. To address this, agencies participating in the National Nanotechnology Initiative (NNI) will create a university-based network geographically distributed across the United States through targeted funding at university centers and in coordination with government laboratories that are part of the NNI. Funding is needed to purchase and provide skilled operators for the network's nanofabrication equipment. While the focus of the program will be to make advances in nanoelectronics, many of the proposed investments in nanoelectronics equipment can also be used for nanotechnology research in solar cell thin films, medical implants, environmental sensors, and other key areas. University research is required to continue American leadership into the nanoelectronics era, and a nanofabrication equipment network is a critical element of this research effort.

Agency Roles and Contributions

Table I. Agency Contributions by Thrust Area

| Thrust Area | NSF | DOD | NIST | DOE | IC |
|--|------------|------------|-------------|------------|-----------|
| 1. Alternative "state variable" for computing | • | • | • | • | • |
| 2. Merging nanophotonics and nanoelectronics | • | • | • | • | • |
| 3. Carbon-based nanoelectronics | • | • | • | | • |
| 4. Quantum information systems | • | • | • | | • |
| 5. National Nanoelectronics and Manufacturing Infrastructure | • | • | • | | |

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