House Committee on Science and Technology

Hearing on the Transfer of National Nanotechnology Initiative Research Outcomes for Commercial and Public Benefit

Written Testimony Submitted
By

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On behalf of
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Good morning. My name is Jeffrey Welser, and I am on assignment from the IBM Corporation to serve as the Director of the Nanoelectronics Research Initiative (NRI). I am testifying today on behalf of the NRI; the IBM Corporation; the Semiconductor Industry Association; and the Semiconductor Research Corporation.

The Nanoelectronics Research Initiative (NRI) is a research consortium that supports university basic research in novel computing devices to enable the semiconductor industry to continue technology advances beyond the limits of the CMOS[1] technology

[1] Complementary Metal Oxide Semiconductor

that we have been using for the past four to five decades. The NRI leverages industry, university, and both U.S. state and federal government funds to support research at universities that will establish the U.S. as the world leader in the nanoelectronics revolution. Fundamental breakthroughs in physical sciences and engineering resulting from NRI leadership will ensure that the U.S. remains a world leader in high-technology.

At IBM, we lead in the business of innovation. IBM takes its breadth and depth of insight on issues, processes and operations across a variety of industries, and invents and applies technology and services to help solve its clients' most intractable business and competitive problems.

The Semiconductor Industry Association (SIA) has represented America's semiconductor industry since 1977. The U.S. semiconductor industry has 46 percent of the $257 billion world semiconductor market. The semiconductor industry employs 216,000 people across the U.S., and is America's second largest export sector.

The Semiconductor Research Corporation is a world class university research management consortium that seeks to solve the technical challenges facing the semiconductor industry and develop technical talent for its member companies. SRC manages several semiconductor research programs, including the NRI. Since its founding 25 years ago, the SRC has managed through its core program in excess of $1 billion in research funds, supporting 6,976 students and 1,598 faculty at 237 universities, resulting in 39,536 technical documents and 302 patents. In July 2007, SRC was awarded the National Medal of Technology by President Bush with a citation recognizing the unique value of this organization: "For building the world's largest and most successful university research force to support the rapid growth and 10,000-fold advances of the semiconductor industry; for proving the concept of collaborative research as the first high-tech research consortium; and for creating the concept and methodology that evolved into the International Technology Roadmap for Semiconductors."

Executive Summary

- Semiconductor technology advances have been credited with driving the increased productivity that the U.S. economy has enjoyed since the mid-1990's.

- The Nanoelectronics Research Initiative (NRI) leverages industry, university and government resources (both state and federal) to fund university research that will keep America at the forefront of the nanoelectronics revolution. NRI, in partnership with the National Institute of Standards and Technology (NIST), currently works largely through three regional university centers headquartered in California, Texas, and New York, as well as with some of the National Science Foundation (NSF) Nanoscience centers across the country.

- The interaction of industry, government, and university researchers in the NRI facilitates the sharing of ideas, enables each partner to focus on its particular strength - such as NIST's expertise in metrology, allows efficient utilization of expensive nanoelectronics equipment, and promotes increased student interest in nanoelectronics. This partnership ultimately will result in faster commercialization of the research results.

- The semiconductor industry strongly supports the reauthorization of the National Nanotechnology Initiative (NNI) to ensure continued critical research and interagency activities in the area of nanoelectronics, specifically. Since current semiconductor technology is approaching its physical and other limits, a new electronic switch must be identified to replace the current technology if the U.S. is to continue receiving the benefits of smaller, faster, and denser electronic devices. The country whose companies are first to market with a new logic switch likely will lead in the nanoelectronics era for decades to come, the way the U.S. has led for the last half a century in microelectronics.

- Current federal funding levels for nanoelectronics-focused research are inadequate in light of the enormity of the research challenge in this area.

- Specifically, the NNI reauthorization should:

1. Explicitly include as a priority program activity the support of nanoelectronics research;

2. Include a request for the National Nanotechnology Coordination Office to develop and implement a plan to ensure U.S. leadership in nanoelectronics;

3. Request that the National Academies include a nanoelectronics study as part of its triennial external review of the NNI;

4. Include specific and higher-than-current authorization levels for nanoelectronics-focused appropriations from within total NNI authorization amounts;

5. Address the need for nanoelectronics research infrastructure, i.e. equipment and equipment operating funds, at universities and national laboratories.

6. Specifically encourage direct industry-government partnerships in support of nanoelectronics research at universities and national laboratories.

<u>NNI should be reauthorized, and include specific and increased authorizations for nanoelectronics</u>

Let me state at the outset that the semiconductor industry strongly supports the reauthorization of the National Nanotechnology Initiative (NNI) to ensure continued critical research and interagency activities on nanotechnology.

The legislation should include specific and higher-than-current level authorizations for nanoelectronics research and equipment. This, in turn, would enable the U.S. to be the first in the world to demonstrate a nanotechnology-based electronic logic switch that is able to replace the solid state transistors that store and process information in integrated circuits. Finding a new switch should be a priority area for the NNI.

Before discussing the importance of the NNI, I should note that the industry's support for increased federal research funding is part of our complete set of competitiveness recommendations, which include increased availability of green cards and H-1Bs visas through immigration reform; increased numbers of science, technology, engineering and math (STEM) graduates; improved K-12, undergraduate and graduate STEM education; enactment of a permanent and enhanced R&D credit; and increased awareness of the impact of foreign tax incentives.

Federally funded basic research, and in particular, funding for nanoelectronics research, is vital to America's future economic growth and global competitiveness. **Simply put, as we approach the fundamental limits of the current technology that has driven the high tech industry, the country whose companies are first to market in the subsequent technology transition likely will lead the coming nanoelectronics era the way the U.S. has led for half a century in microelectronics**. NNI can play a critical role in ensuring that America earns this leadership position.

Today I would like to address four topics:

- the technical challenges we have as we move to the nanoelectronics era;
- why U.S. leadership in nanoelectronics is vital to our nation;
- the Nanoelectronics Research Initiative (NRI), as an example of industry-government collaboration that can be furthered by the NNI; and
- policy recommendations that should be included in the NNI to help maintain U.S. leadership in nanoelectronics.

To continue semiconductor technology advances, we must find a new switch

Semiconductors are the enabling technology for computers, communications, and other electronics products that, in turn, have enabled everything from internet commerce to sequencing the human genome.

Better, faster, and cheaper chips are driving increased productivity and creating more jobs throughout the economy. For over three decades, the industry has followed Moore's Law, which states that the number of transistors on a chip doubles about every eighteen months. The transistor is the basic building block within the semiconductor chip and can be thought of as an electronic switch or as a device to retain one bit (a one or a zero) in memory. The transistor is composed of a series of precisely etched and deposited layers of materials, and with as many as two billion transistors integrated on a single silicon chip, modern computer chips are the most complex product manufactured on the planet.

The phenomenal advances in technology may slow drastically as semiconductor technologists have concluded that we will soon reach the fundamental limits of Complementary Metal Oxide Semiconductor (CMOS) technology, the process that has been the basis of innovation for the semiconductor industry for the past 30 years. By introducing new materials into the basic CMOS structure and devising new CMOS structures and interconnects, further improvements in CMOS can continue for the next ten to fifteen years, at which time, CMOS begins to reach its physical (layers only a few atoms thick) and power dissipation limits. For the U.S. economy to benefit from continued information technology productivity improvements, there will need to be a "new logic switch" to replace the current CMOS-based transistor.

There are a number of candidates for the new switch, including devices based on spintronics (changing a particle's spin) and molecular electronics (changing a molecule's shape). Scientists must address many challenges in many different basic research fields (chemistry, physics, electrical engineering) in the search for the new switch. The challenges include:

- measuring the dimensions, shapes, and electrical characteristics of individual molecules;
- manipulating and measuring the spin of individual electrons;
- fabricating whole new classes of materials with unique electronic properties, and then characterizing their fundamental physical behavior and their long-term reliability;
- inducing novel chemical compounds to self-assemble into the precise structures needed by the new devices and architectures, and doing so in a way that can be manufactured at commercial volumes;

- developing complex circuits to take advantage of, or overcome limitation of, the properties of the new devices; and

- finding ways to interconnect the devices and integrate them into our technology infrastructure in a cost-effective manner, which will enable us to continue the historical cost and performance trends for information technology.

Note that addressing these challenges not only will require the best minds from industry and academia, but it also requires new equipment for fabricating and characterizing these nanostructures. While existing facilities at university centers already enabled by NSF's continuing investment in the National Nanotechnology Infrastructure Network (NNIN) can be used, significant *additional* investment in new specialized equipment is required, particularly to enable the realistic prototyping of new nanoelectronic devices and circuits. This will be crucial to transitioning these into both commercial and manufacturing environments.

U.S. leadership in nanoelectronics is vital to our nation

As stated earlier, the country that finds a new logic switch undoubtedly will lead in the nanoelectronics era. Moreover, this leadership will have widespread impact across our entire technology and science-driven economy, since nanoelectronics have significant applications in information technology, communications, medicine, energy, and security.

Research investments to continue the increased circuit density described in Moore's Law have immense benefits to the U.S. economy. Moore's Law has resulted in a 65% drop in the price of a computer over the past 10 years, while increasing the computer's speed, memory, and functionality. Harvard economist Dale Jorgenson has noted, "The economics of Information Technology begins with the precipitous and continuing fall in semiconductor prices." Professor Jorgenson attributed the rapid adoption of IT in the U.S. to driving substantial economic growth in the U.S. gross domestic product since 1995, concluding, "Since 1995, Information Technology industries have accounted for 25 percent of overall economic growth, while making up only 3 percent of the GDP. As a group, these industries contribute more to economy-wide productivity growth than all other industries combined."[2]

To see the impact of the productivity gains on a single sector, it is instructive to consider the benefits the government (federal, state, and local) receives as a consumer of semiconductors. The Department of Commerce's Bureau of Economic Analysis has data indicating that the government sector of the economy purchased $8 billion of computers in 2006, but that it would have had to spend $45 billion for that same amount of computing power if it were paid for in 1997 prices. The cumulative benefit from technology improvements and resulting price declines from 1997 to 2006 is $163 billion

[2] Dale W. Jorgenson, "Moore's Law and the Emergence of the New Economy" in "2020 is Closer than You Think"; 2005 SIA annual report.

of “free” computing. In this tight budget environment, it is important to remember that federal investments made to support basic research not only are beneficial to the overall U.S. economy, but they also allow the government itself to do more with less as a result of falling computing costs.

Nanoelectronic computing also will have benefits in medicine and energy. It is not an overstatement to say that mapping the human genome is as much a success of computer science as biology, and future challenges such as modeling protein folding and creating cheaper and clearer MRIs and 3D X-ray imaging will require continued advances in computing speed. The Technology CEO Council has documented the effects of improved information technology on improving energy efficiency, which advances U.S. energy security and climate change policies. While automobiles’ miles per gallon have improved 40 percent since 1978, and replacing a 1978 incandescent bulb with today’s compact fluorescent bulb improves the lumens per watt by 339 percent, the improvement in computer systems’ instructions per second per watt since 1978 has increased 2,857,000 percent.[3] Continuing these trends into the nanoelectronics era is absolutely essential to continue the improvements in U.S. energy intensity (increased economic output per unit of energy). In addition, many of the technologies developed to further the semiconductor chip industry now are utilized in new innovations for the renewable energy sector, most notably to develop cheaper and more efficient solar cells.

So too, nanoelectronics computing is important for national security. Precision weapons, satellite imaging, submarine detection, secure global communications, monitoring of adversaries’ communications, and real time identification of allies’ positions to avoid friendly fire casualties are but a few of the examples of why many people consider leadership in semiconductor technology to be in the nation’s security interests. Indeed, the original semiconductor diode was implemented as a mission-critical project at universities and industrial labs in the 1940’s, funded largely by the Department of the Defense because it recognized the urgency of being the first country to have this technology in its weapon systems.

Finally, it should be emphasized that all of these commercial benefits only will be realized if we invest heavily *now* in basic nanoelectronics science and engineering. Many of the breakthrough products and innovations we see today are being built on basic research that was done in the 1990’s. With more federal money focused on near-term – rather than long-term – research projects, the country runs the risk of under-funding the basic research pipeline which our industries rely on for future innovations.

Fortunately, the House Appropriations Committee recognized nanoelectronics as a priority area when it singled out NSF’s work with the Nanoelectronics Research Initiative in its FY2008 committee report, stating:

[3] Technology CEO Council, “A Smarter Shade of Green – How Innovative Technologies are Saving Energy, Time, and Money,” 2008.

> "Given the economic importance and pervasive impact of semiconductors, the Committee supports NSF's continued sponsorship of the Nanoelectronics Research Initiative and other programs to advance semiconductor technology to its ultimate limits and to find a replacement technology to further information technology advances once these limits are reached. The Committee encourages NSF to continue its support for such research in fiscal year 2008." [4]

<u>The NRI is an industry-university-government partnership to find a new switch</u>

As the laws of physics narrow the potential for the kind of scaling that historically has characterized the semiconductor industry, attention has turned to the discovery of a new logic switch as a means to continue the progress depicted by Moore's Law. To take on the daunting task of identifying and demonstrating the commercial feasibility of a new logic switch, the SIA launched the Nanoelectronics Research Initiative (NRI).

The NRI pulls together semiconductor companies[5], the National Science Foundation, the National Institute of Standards and Technology, state governments, and 25 universities in 13 states with about 60 professors and 70 students/post docs. The industry contribution through the NRI is over $5 million per year; this is in addition to about $60 million that the semiconductor industry invests in universities through other research consortia, with millions more invested directly by individual companies.

The research activity is organized within three NRI university centers that were established in 2006, plus NRI and NSF supplemental co-funding of nanoelectronics projects at 10 existing NSF university centers. The three NRI university centers are virtual centers, grouped largely by geography. While all of the centers are working on research aimed at discovering a new logic switch, the focus of the programs at each center has its own specific character:

The Western Institute of Nanoelectronics (WIN) is headquartered at UCLA and includes UC Berkeley, UC Santa Barbara, and Stanford University. WIN focuses solely on spintronics and related phenomena, extending from material, devices, and device-device interaction all the way to circuits and architectures. In addition to its NRI funding, this center receives additional direct support from Intel and California's UC Discovery program.

The Institute for Nanoelectronics Discovery and Exploration (INDEX) is headquartered at the State University of New York-Albany (SUNY-Albany) and includes the Georgia Institute of Technology, Harvard University, the Massachusetts Institute of Technology, Purdue University, Rensselaer Polytechnic Institute and Yale University. INDEX focuses on the development of nanomaterial systems; atomic-scale fabrication technologies; predictive modeling protocols for devices, subsystems and systems;

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[4] House Report 110-240 - Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2008.

[5] The semiconductor companies funding the NRI are Advanced Micro Devices, Freescale, IBM, Intel, Micron Technology, and Texas Instruments.

power dissipation management designs; and realistic architectural integration schemes for realizing novel magnetic and molecular quantum devices. INDEX also receives additional direct support from IBM and New York State.

The South West Academy for Nanoelectronics (SWAN) is headquartered at the University of Texas–Austin and includes UT-Dallas, Texas A&M, Rice, Notre Dame, Arizona State and the University of Maryland. SWAN focuses on a variety of new devices, including spin-based switches, nanowires, nano-magnets, and devices which use electron wave or phase interference. In addition, work is being done on modeling; novel interconnects, such as plasmonics; and nano-metrology techniques. In addition to its NRI funding, SWAN receives additional support from Texas Instruments and the Texas Emerging Technology Fund.

In addition to these centers, NRI and NSF co-fund supplemental grants for NRI-related research at existing NSF nanoscience centers, Nanoscale Science and Engineering Centers (NSECs), Materials Research Science and Engineering Centers (MRSECs), and the Network for Computational Nanotechnology (NCN). We currently are supporting 12 projects at 10 NSF centers, which range from advanced computer simulation of spin-based devices to measurements of non-equilibrium coherent transport in single-layer graphene sheets to directed self-assembly of quantum dot and wire structures for novel devices. The goal in making this joint investment with NSF is not only to complement the work going on in the NRI centers, but also to jointly leverage the knowledge gained from work going on in both NSF and NRI centers.

NSF's involvement with nanoelectronics was highlighted by the recent announcement of the Science and Engineering Beyond Moore's Law initiative in the President's FY2009 budget request. The $20 million request "will support research to develop the next generation of materials, algorithms, architectures and software with capabilities far beyond those available today, and governed by new empirical laws. With these advances, computing power will become even more concentrated, integrated and ubiquitous."[6]

In 2007, NIST concluded an open competition by entering into partnership with the NRI to accelerate research in nanoelectronics. Under the partnership, NIST and NRI will jointly provide $18.5 million over five years toward high-priority university research projects identified by industry and NIST researchers. NIST scientists and engineers have been leaders in nanoelectronics research, especially in the science of measurement. The partnership implements the conclusion of NIST's major February 2007 report which called for the development of measurement techniques for frontier technologies such as post-CMOS electronics.[7]

[6] Remarks by NSF Director Arden Bement, Jr.; Presentation of the NSF FY 2009 budget request to Congress; February 4, 2008.

[7] NIST, "An Assessment of the United States Measurement System", February 2007, http://usms.nist.gov.

The NRI complements another government-industry partnership, the Focus Center Research Program (FCRP). This program is cosponsored by the semiconductor industry and the Department of Defense to fund research at 38 universities. It seeks to advance the current CMOS chip technology to its ultimate limits, while the NRI's objective is to go beyond the limits of the current technology. Both the NRI and FCRP are administered by the Semiconductor Research Corporation (SRC), a non-profit consortium of companies representing of the full spectrum of the semiconductor industry. The SRC also administers the Global Research Collaboration (GRC), which funds a large research program focused on addressing the challenges in the nearer term semiconductor roadmap, crucial to continuing the rapid rate of industry innovation.

While still in its early stages, the NRI already is beginning to show results with over 100 technical publications and 5 patent disclosures. As the research begins to come to fruition, prior industry involvement will facilitate technology transfer, even before the ultimate goal of finding a new switch is realized. An example of this kind of early commercialization due to close industry-university work outside of NRI is the air gap wiring announcement made by IBM in 2007, based on work being done at the Albany Nanotech Center. It is a very early application of self-assembly, which has been actively researched for many years, in a real product in an unexpected way, and it points out the importance of universities and industry working together. Rapid commercialization of academic research is in the interest of universities and government funding agencies, as well as industry, as it directly contributes to American competitiveness. The NRI is building on 25 years of experience by its parent, the SRC, in managing university research, in partnership with industry and the government.

Industry-Government-University Roles in Nanoelectronics Research

From the beginning, the NRI has welcomed input from the government on our overall program, and it would like to see these partnerships *increase* going forward. NSF, DARPA, and NIST attend the NRI's Governing Council meetings. The Council provides executive oversight to the program. Due to the magnitude of the scientific challenges ahead and the large diversity of scientific disciplines required, government expertise and resources are absolutely critical.

The overall model for the NRI is to do mission-focused basic research at multi-university centers. This best balances the need for a broad range of research into many different science phenomena with the need for a clear goal to drive the research in the most productive directions. Five research vectors are used to provide a concrete framework for the mission focus, as well as focus the work on the overall goal of finding a new logic switch. These vectors, distilled from an initial list of thirteen, were considered the top research priorities based on a series of industry-government-university workshops and studies conducted by SRC, SIA, and NSF.

Centering the work at multi-university centers – rather than in industry or national labs – is crucial not only for driving the research, but also to expand the number of students and the capability of universities engaged in nanoelectronics-related research. This will sustain and expand the industry in new directions in the future. It is equally important to set up several of these centers across the U.S. to engage the largest number of top researchers at many different universities. To this end, we are currently looking to open a fourth NRI center later this year in the Midwest, complementing the three existing centers in the East, West, and Southwest.

We have used two models to enable the multi-university work. With the NSF, we jointly fund research in existing NSF nanoscience centers. These projects are chosen by independent reviews by the NRI industry team and the NSF itself. An industry liaison team is assigned to interact with the centers and give industry input on the individual projects as well as the overall center research. This model works well for leveraging the significant NSF investment in these centers, helping to guide that work towards areas we think will have large potential for future commercialization and giving us a broad view on many emerging areas of research.

At the NRI centers themselves, we take this partnership model even further, both for joint funding and technical guidance, with the hope of accelerating the discovery process. Initially, the multi-university centers were set up geographically, and strong partnerships were developed with state governments for funding the work. The state partnership is unique in that states not only are providing several million dollars annually to their universities to support the NRI research, but they also are investing hundreds of millions into new Nanoelectronics buildings, centers and infrastructure to enable the next generation of this research. Examples includes the New York Albany NanoTech center (www.albanynanotech.org), the California NanoSystems Institute (www.cnsi.ucla.edu), as well as major support for recruiting and endowing new faculty for Nanoelectronics research in Texas. These investments are focused not simply on enabling the research, but also on enabling the rapid commercialization of any new technologies that emerge from the research. Hence, this support is crucial to translating discovery into product innovation.

And the states are investing for the same reason the NNI needs to be investing: economic competitiveness. The transition to a new switch will be challenging and uncertain, meaning that the companies, states, and universities that benefited from the previous technology era may not be the ones to lead in the new era. State governments see this transition point as an opportunity to grow an entirely new industry around their university base to drive their economies, the same way Silicon Valley grew up around the transistor.

The NIST agreement extends the work in the NRI centers to now include a federal partner in a unique technical, management, and funding role. We think this should be a model for future engagements. A Technical Program Group (TPG), consisting of members from both NIST and industry, evaluates the project proposals to determine where the funds from both groups will be invested in the universities, as well as oversees the on-going research through a variety of mechanisms. The TPG has monthly meetings to make decisions on the overall program, and sub-teams from the

TPG meet monthly with the lead professors from each of the NRI centers to discuss the progress of the technical work and center logistics in detail. Moreover, the industry has full-time assignees working alongside the professors and students at each of the centers to provide daily input and guidance on the research. In addition to the usual publication of results in technical journals and conferences, the centers also hold annual on-site reviews and produce semi-annual reports for both the NRI industry members and NIST. Lastly, we intend to strongly leverage the expertise and facilities within the NIST labs themselves, by having university researchers at the NRI centers work directly with the labs on projects to advance the NRI mission.

Nanometrology and characterization are key to any advances in nanoelectronics – particularly in trying to link experimental work to theory. The partnership with NIST should open the door not only to utilizing the existing NIST facilities, but also to help guide their continued work on new characterization tools to those most vital for developing and characterizing the next generation of nanoelectronic devices. For example, it is now becoming possible to measure the spin of an individual electron, but to truly characterize spintronic devices, we would want to be able to track that spin's evolution as it is manipulated in the switch itself. This is precisely the kind of grand challenge that NIST is uniquely suited to undertake. By working closely with NRI university and industry researchers, the results of this new capability will have much more rapid impact on new device and product development.

While the NIST labs – and the other national labs – offer a very valuable resource for enabling nanoelectronics research, we continue to believe it is equally important to invest federal funding in state-of-the-art facilities directly at the universities themselves. While some work, such as characterization utilizing large neutron or synchrotron radiation, can be done most efficiently at the national lab facilities, much device and materials research relies on daily work in a facility local to the university, where the students are working directly with their professors and other group members. This cannot easily be replicated remotely. To balance the desire to have easy access by the largest number of faculty and students with the large investment costs, having an extended network of nanoelectronics infrastructure capable of fabrication, characterization, and early prototyping at a number of multi-university centers (such as NNIN) is particularly effective. And with the NRI model, the states and universities are already doing their part to invest in new buildings and base infrastructure. What they need is expanded federal funding to match their investments for equipment and on-going support.

To summarize, we feel the NRI model for direct partnering between industry, government, and universities is the most effective way to conduct mission-oriented basic research that most rapidly leads to new product innovations. And far from hindering basic science research, this close early industry involvement can actually accelerate it in promising directions. As an example, at one of the first NRI reviews, a professor presented work on a new phenomenon he dubbed "pseudospintronics." As a physics professor looking to understand the basic science, all of his work had been at very low temperatures. After discussions at the review with other engineering professors and industry researchers on the potential for this phenomenon to be utilized in a future device, he continued his basic research, but he also focused on understanding its extendibility to room temperature. By the next review, he not only had several exciting new insights into the science, but he had ideas about how it could be made more robust for higher temperature operation. He even had a novel idea for a new logic switch based on the effect. This experience is precisely the kind of new thinking that comes from conversations between the science and engineering worlds (and the industrial and academic worlds) that NRI hopes to foster, and it ultimately will result in faster commercialization of the ideas it produces.

Building on the government-industry NRI partnership: recommendations for the NNI

As outlined above, the obstacles for identifying a viable new switch are daunting, but the benefits of being the leader in this new technology are huge. The semiconductor industry supports the reauthorization of the National Nanotechnology Initiative to ensure continued critical federal research and interagency activities on nanotechnology. The industry specifically recommends that Congress include the following:

1. The NNI reauthorization should explicitly include as a priority program activity the support of a research, development and demonstration program in nanoelectronics.
    - The National Nanotechnology Coordination Office and the federal agencies that participate in the National Nanotechnology Initiative should be asked to develop and implement a plan for the above activity, with the goal of ensuring that U.S. researchers are the first in the world to demonstrate a nanotechnology-based electronic logic switch that is scalable, reliable, low-power, capable of being manufactured in commercial volumes, and potentially able to replace solid state transistors in integrated circuits.

2. The NNI reauthorization should require that the National Academies include, as part of its triennial external review of the NNI, a study on nanoelectronics research opportunities. The study should identify the most promising research opportunities in the application of nanotechnology to electronic logic switches. The study also should include a recommended research and development roadmap for federal agencies that conduct or support nanoelectronics research.

3. The NNI should include specific and higher-than-current-level authorizations for nanoelectronics appropriations from within the NNI authorization amounts for the NSF, NIST, and Department of Energy. The authorizations should reflect the pervasiveness of information technology in the U.S. economy, IT's impact on U.S. economic growth, and the magnitude of the challenges involved in identifying and demonstrating an electronic switch capable of replacing our current technology.

4. The NNI reauthorization should address the need for nanoelectronics research infrastructure, i.e. equipment and equipment operating funds, in addition to funding for research. This applies not only to authorizations for NSF to support infrastructure at our nation's universities, but also to NIST for equipping and operating the equipment for the nanoelectronics research at the Gaithersburg and Boulder labs.

5. The NNI Reauthorization should specifically encourage direct industry-government partnerships in support of nanoelectronics research at universities and national laboratories. These partnerships promote cross-fertilization of ideas, facilitate technology transfer and ultimately commercialization of nanoelectronics devices, as well as promote potential economic development around nanoelectronics research clusters.

Summary

Discovering, developing, and implementing a new logic device is a daunting task, but it is not unprecedented. In the 1940's, when vacuum tubes were state-of-the-art but reaching their own limits, the U.S. government realized a critical need for finding smaller, faster, and lighter devices for its radar and guided missile systems. The result was not only technology to enable advanced weapon systems, but the birth of the solid-state transistor, which became the foundation of the information technology revolution that drives our economy to this day. It was the combination of the best basic science research coming out of the universities, the practical guidance and mission-focus of the industrial labs, the significant research funding from the government, and the collaborative interaction of all of these groups that enabled both the scientific breakthroughs and the reduction to practical implementation necessary for such a project to succeed.

As we look for a switch to replace our current CMOS transistor, we now face a similar transition. We are just beginning this research, and the initial efforts are small in comparison to what was done in the 1940's and 1950's. It is critical we grow these efforts significantly over the next several years, and finding flexible models for industry and government to interact will be critical to success. To this end, increasing attention and research funding in the nanoelectronics area are absolutely essential if we are to continue our accelerated economic growth and productivity, thereby enabling America to lead in the coming nanoelectronics era.