Spring 2009
Industry Study

Final Report
Electronics Industry

The Industrial College of the Armed Forces
National Defense University
Fort McNair, Washington, D.C. 20319-5062

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Spring 2009. Industry Study. Electronics Industry**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Defense University,The Industrial College of the Armed Forces,Washington,DC,20319**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**35**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ELECTRONICS 2009

ABSTRACT: The semiconductor industry is under pressure, thus accelerating the industry evolution from vertical integration to specialization and collaboration. Speed-to-market, function integration, low power, and customer focus are increasingly important. Clustering and collaborative efforts are needed to offset the high costs of new development and are necessary for knowledge fusion and cross-disciplinary research. The US currently lacks a comprehensive plan to fully capitalize on opportunities presented by the new environment and ensure continued leadership. The US needs strategies to retain top intellectual talent, bolster industry-leading R&D, set conditions for success within American borders, and secure the supply chain for DoD requirements.

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Domestic

National Capitol Region
BAE Systems Space Systems & Electronics, Manassas, VA
Capitol Hill, Washington, DC
- Senate and House Armed Services Committee
- House Science Committee, Technology and Innovation Subcommittee
- Institute for Defense Analysis (IDA)

ICAF Seminar
- Department of Commerce
- Semiconductor Industry Association (SIA)
- National Security Agency (NSA)
- Naval Research Laboratory (NRL)
- National Institute of Standards and Technology (NIST)

International Business Machines (IBM), Washington, DC
- TechAmerica
- Texas Instruments (TI)
- Semiconductor Research Corporation (SRC)
- Semiconductor Equipment and Materials International (SEMI)

National Institute of Standards and Technology (NIST), Gaithersburg, MD
National Security Agency, Fort Meade, MD
Naval Research Laboratory, Washington, DC
Northrop Grumman, Linthicum, MD
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New York
International Business Machines
- Yorktown Heights – Watson Research Center
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California
Advanced Micro Devices (AMD), Sunnyvale
Applied Materials, Sunnyvale
Defense Micro Electronics Activity (DMEA), Moffett Field
Electronic Design Automation Consortium (EDA), Sunnyvale
- Cadence, Mentor Graphics, Synopsys

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International

Taiwan
Advanced Semiconductor Engineering Company (ASE)
American Institute in Taiwan (AIT)
American Chamber of Commerce, Taipei
Etron Technology, Inc.
Industrial Technology Research Institute (ITRI)
Nanya Technology Company
Sunplus Technology Company
Taiwan Semiconductor Industry Association (TSIA)
Taiwan Semiconductor Manufacturing Company (TSMC)
United Microelectronics Company (UMC)

People's Republic of China
Chinese Semiconductor Industry Association
IBM China Research Lab
Lenovo Group
Semiconductor Industry Association, Beijing
Semiconductor Manufacturing International Corporation (SMIC)
US Consulate, Shanghai
US Information Technology Office

INTRODUCTION

No other invention in the past fifty years has had a more profound impact on American society than the semiconductor. Semiconductor-based electronics have enabled scientific advancement which in turn has led to the development of an astonishing range of goods and services. The rapid growth in the functionality and speed of integrated circuits (ICs) has enabled tremendous gains in productivity across all sectors of the US economy.[1] The production, sale and consumption of these goods and services has spurred economic growth and created high-wage jobs.[2] The proliferation of semiconductor-based electronics has significantly improved the American quality of life and standard of living. In addition, semiconductors have become absolutely critical to American National Security, as they form the foundation for space, communications, and weapons systems that enable global engagement.

Because a vibrant, leading-edge semiconductor industry is essential to US national security, the Industrial College of the Armed Forces (ICAF) has performed an in-depth, but by no means exhaustive study of the industry to understand the challenges the industry is facing and examine its outlook. The ICAF Electronics Study seminar, composed of 16 ICAF students and 3 faculty members, has invested a significant amount of time listening to and questioning leading industry and government experts. We have had the good fortune to discuss current issues with over 50 leading industry speakers, laboratories, corporations, and government entities. We have been extremely fortunate to examine parts of the global industry through domestic and international travel. We have visited sites in the National Capitol Region, New York State, Silicon Valley California, Taiwan, and the People's Republic of China. During the course of the study we have examined the industrial value chain, the current technology state-of-the-art, public policy issues, defense-specific issues, business models, and the impact of the current economic conditions on the industry.

In the course of the study, we observed major industry structure and current market shifts. The effect of globalization on trade, the increased requirement for capital, and the dominance of a few titans at the leading technology node have accelerated the evolution from a vertically-integrated industry to an industry of specialization and collaboration. In addition, those factors and the desire to establish competitive advantage in niche segments have pushed the broader market to focus more on consumer demand through product-based development. Improving performance through scaling will continue to be important, but improving performance by other means to gain relative competitive advantage is gaining importance. Although recent public policy changes have somewhat improved the environment, especially in regards to basic research and development, the US lacks a comprehensive and synergistic plan to fully capitalize on opportunities presented by the new environment and ensure continued leadership in a post-CMOS and multidisciplinary nanotechnology environment.

We will develop these observations, and others, in the course of this paper. We are first going to establish context for the industry study through a definition of the semiconductor industry and description of the current conditions. We will follow with a discussion of the challenges that globalization, rising costs, and an evolving industry structure present and the outlook for the future of the industry. Next, we will provide some short essays on relevant topics to include a discussion of Department of Defense (DoD) requirements for a secure (trusted) value chain. Finally, we will provide some recommendations for US Government and industry action to preserve our current leadership position where we have it and to create favorable conditions for industry leadership in the future.

THE INDUSTRY DEFINED

The semiconductor industry is the aggregate collection of companies engaged in designing, manufacturing, packaging, and testing semiconductor devices. In 2008, the US semiconductor industry continued to dominate the world market with $120B in sales, and a market share of 48% (world wide sales = $249B).[3] More than three quarters of US-owned chip manufacturing capacity is located in the US, however, nearly 77% of revenue is generated from export sales.[4] During the years 2003-2006 semiconductors were the largest US export and second largest export in 2007-2008.[5] In 2008, the US industry employed over 216,000 people.

The industry produces four main products: memory chips, microprocessors, commodity ICs, and "Systems on a Chip" (SoC).[6] Memory chips store data and pass information to and from the computer's microprocessor. Overcapacity in the memory market has led to near zero profit margins for leading manufacturers to include Toshiba, Samsung, and NEC.[7] The microprocessor is a central processing unit containing hundreds of millions of transistors and logic to perform computational tasks.[8] Intel is the dominant producer with 80% of the market share as of September 2008 followed by Advanced Micro Devices. Commodity ICs are produced in large batches for routine processing purposes and are used in consumer devices such as MP3 players, cell phones, and GPS receivers.[9] Asian chip manufacturers such as Taiwan Semiconductor Manufacturing Corporation (TSMC) and Semiconductor Manufacturing International Corporation (SMIC) dominate this product segment accounting for 65% of the market share.[10] The more complex SoC product incorporates functions performed by several chips onto a single IC. As an example, the latest handheld communication devices contain a SoC capable of performing phone, internet, and camera functions.

The primary segments of the semiconductor value chain include design, mask generation, fabrication, packaging, and testing (Figure 1). "Design" includes the use of Electronic Design Automation (EDA) to create complex IC blueprints. Companies that specialize only in this sector are known as "fabless" since they do not manufacture the chips they design. Mask generation transfers the chip design to glass plates used in photolithography. Normally chip production requires several masks each costing $1M or more. Fabrication is the actual manufacturing of the chips and is very capital intensive due to the high cost of the facilities and equipment. A leading-edge "fab" can cost upwards of $5-7B to construct and resource. Packaging and testing involve cutting wafers into individual die, packaging them into substrates, and validating performance.

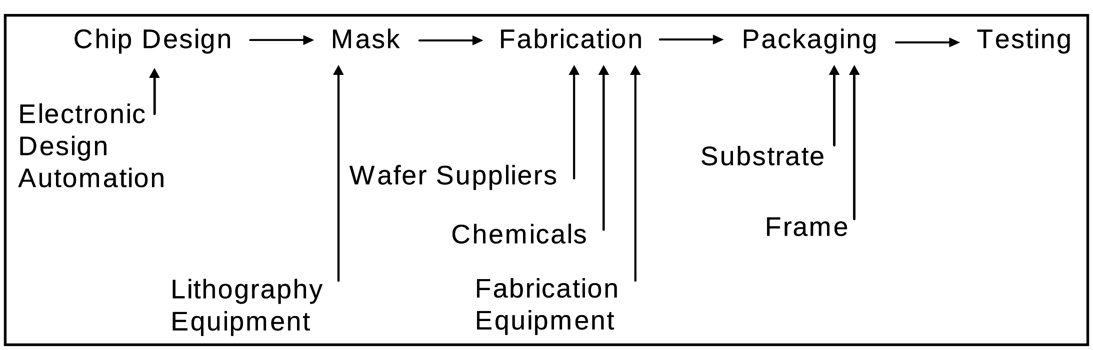

Figure 1. Semiconductor Industry Value Chain

. CURRENT CONDITION

The US semiconductor industry is in the midst of a cyclical downturn exacerbated by the greater global economic recession. Even without the impetus from a global recession, the industry would have undergone a significant shakeup and restructuring resulting from fierce global competition and rapid increase in capital requirements to continue leading technology product development. The current recession, which began in November 2007, has not been a normal recession.[11] Historically, the credit intensive semiconductor industry has followed normal business cycles through recession and expansion. However, this recession is different in that it has been driven not only by a significant reduction in consumer demand but also by the lack of available credit. Companies have been forced to pay substantially higher costs for credit.[12]

The slowing business climate and resulting slow growth of GDP will be a drag on the industry for the next few years. The semiconductor industry is expected to see a decline in revenues of about 19% for 2009 from 2008.[13] Even with the pervasive distribution of semiconductors into almost all goods, reduced demand will result in reduced cash flow for the industry. Global semiconductor chip manufacturers' net income year over year for the 4th quarter, 2007 to 2008, reported a change from a profit of $1.5B to a loss of $8.1B.[14]

Orders for PCs, mobile phones, and other consumer electronics have significantly slowed. Manufacturers and distributors have aggressively reduced inventories, but demand has been falling even faster.[15] The industry is matching manufacturing output to customer demand.[16] This has resulted in historically low semiconductor inventories. Consequently, when the demand for consumer products eventually rebounds, the semiconductor industry will face intense demand for increased production due to the depleted inventory levels.

Current Technology Node

The current state-of-the-art "node" for traditional complementary metal-oxide-semiconductors (CMOS) is 45 nanometers (nm), which refers to the standard gate length for a single silicon transistor. As line width continues to decrease, the classical laws of physics begin to give way to those determined by quantum mechanics. As gate widths are scaled below 100 nm, CMOS devices become susceptible to quantum tunneling and thermal leakage currents resulting in decreased performance.[17] These two fundamental factors, quantum tunneling and thermal leakage currents, will ultimately limit scaling, but before they do, they will drive increasingly elaborate and expensive designs to reach each successive node.[18]

As the costs to implement the next technology node dramatically increase, only the major semiconductor companies can pursue these technologies. These companies, Intel and IBM in particular, are investing billions of dollars annually in research and development to ensure they are the first to market with products at the next node. Intel and IBM are considered integrated device manufacturers (IDMs), because they perform all elements of the value chain, from design through marketing, in-house IDMs are vertically integrated compared to other semiconductor companies which specialize in only one segment of the IC value chain such as design, fabrication, or packaging and test. Many of these specialized companies do not pursue leading edge technologies; however, they achieve performance improvement through other means. For example, specialized companies develop SoC products or products with multiple ICs "stacked" in a single package called a "system in a package" utilizing technology that is a node or two behind the leading edge. These companies offer customers tremendous value through tailored system design, often leveraging others' intellectual property (IP) through license agreements.

Another method of achieving performance through means other than scaling is to organize specialized IC companies into a cluster to achieve vertical integration. This construct is termed clustered virtual-vertical integration (CVVI). A clustered integration structure allows companies from different specialty segments of the value chain to form alliances or partnerships to realize effective vertical integration at reduced costs, as each segment optimizes operations to achieve maximum efficiency. The rapid IC design cycle requires companies in a cluster to engage each other early on to co-define specifications and to begin co-development. The Taiwanese IC industry illustrates the best example of a world class IC CVVI concept. Specifically, TSMC co-develops advanced-technology designs with their cluster partners.[19]

Design Segment

New IC development starts with a new design. Software tools are required to develop circuits with a transistor count approaching one billion. Three US companies dominate the worldwide electronic design automation (EDA) industry – Cadence, Synopsys, and Mentor Graphics – accounting for 75% of the market share.[20] More than 400 US companies operate within 66 niches that make up the design segment.[21] According to the EDA Consortium, the global semiconductor design revenue for 2008 was $5.3B, a 9.0% decrease from 2007.[22] The compounded annual growth rate for the US portion of the industry since 2002 has been 3.3% versus 7.1% worldwide.[23] Although the US leads in innovative chip design and design software, other parts of the world are gaining capability. Increasingly, design centers are moving east to India, China, and Taiwan. According to Clair Brown and Greg Linden of the University of California, Berkeley, "location decisions for chip design are based on three primary factors related to competitive advantage: closer contact with customers, access to specialized skilled labor, and cost reduction."[24] For example, as the manufacturing of consumer items has moved to Asia, so have some of the Application-Specific Integrated Circuit (ASIC) design companies.[25] Moreover, the CVVI concept in Taiwan allows designers, and manufacturers to get closer to their customers. Many foreign companies, however, have maintained a presence in US design centers in order to take advantage of the high skills and productivity there as well as maintain access to US customers.[26] Some US EDA companies are forming partnerships with their customers, leading IP vendors, and foundries similar to the CVVI concept.[27]

Semiconductor Supplier Segment

The semiconductor supplier segment includes those companies that provide production and facility equipment, process materials, packaging materials, consumables and components, software and factory automation, fabrication facilities design and construction, and consulting services.[28] Equipment for the wafer processing segment makes up the vast majority of the industry at 74.2% of market share. The global semiconductor equipment market shrank by 27.7% in 2008 to $30.9B due to the lack of demand caused by the global recession.[29] US companies account for 18.1% or $5.6B of the market; however, more than 78% of their sales are overseas.[30] The market is cyclical and closely tied to IC demand. IC demand has declined and is expected to drive down semiconductor equipment orders until at least 2010. Four companies account for 77% of the market share. The market share for these four companies are as follows:[31] Tokyo

Electron – 28.5% (Japan), Applied Materials – 26.2% (USA), ASML Holding NV – 13.9% (EU), KLA-Tencor – 8.1% (USA). In the long term, the market is forecast to accelerate with a compound annual growth rate of 7.6% for the period 2008-2013.[32]

Chip Manufacturing Segment

The US share of the worldwide chip fabrication capacity has declined from 33% in 1997 to just 16% in 2007.[33] In 2008 US share of the market increased slightly to 17%.[34] Competitive pressures along with tax incentives, government subsidies, and forecast demand in expanding economies in China and India have led US companies to build fabrication facilities overseas or to rely on foreign pure play foundries rather than invest in new facilities in the US.[35] In 2008, the US chip manufacturing industry generated revenues of $42B, a 4.7% decline from 2007.[36] For the period 2004-2008 the US semiconductor market grew at a 1.5% compounded annual rate.[37] By comparison, the Asia-Pacific market grew 6.5% during the same period reaching $155B in revenue in 2008. The US market is forecasted to accelerate 3.1% during the period 2008-2013 while Asia-Pacific will grow 6.0% and Europe 2.1%.[38] The integrated semiconductor segment made up 97% of the US chip market generating $40.4B in revenues in 2008 while discrete semiconductors made up the remaining 2.7% or $1.1B in revenue.[39] Intel is the clear US and world market leader in the chip manufacturing business with an 11.7% market share followed closely by Samsung with a 10.3% market share.[40] Intel is the leader in the production of microprocessors while Samsung is the leading memory chip producer. Other US chip manufacturers include Texas Instruments (TI), Advanced Micro Devices (AMD), Micron, Freescale, IBM, and Alliance.

Consumer Demand and Rising Costs Impact Business Models

The Semiconductor Industry Association (SIA) 2009 forecast anticipates consumer electronics will comprise 79% of the IC market. The remaining 21% will be dedicated to the industrial market with about 1.0% for the global defense industry.[41] The IC market shift toward consumer electronics in association with the CVVI concept has encouraged a regional concentration of IC value chain from IC design through final assembly of the consumer end item. The increasingly disposable nature of consumer electronics has shortened the lifecycle of IC components, thus requiring more rapid design to consumer demand. The CVVI concept enables a rapid development cycle, giving the Asian consumer market IC producers a competitive advantage over their US counterparts. Moreover, the CVVI concept has been encouraged through government intervention, specifically in the area of fabrication construction, low interest loans, tax incentives, and subsidies.

The large capital investment to construct a fabrication facility at the leading node has resulted in US semiconductor companies favoring outsourcing chip manufacturing. As an example, TI announced that it will no longer manufacture chips in-house, but will partner with TSMC and UMC for the fabrication process.[42] Other US companies have chosen to build fabs overseas in order to be closer to their end-market customers. Other issues faced by US chip manufacturers include: the eroding average selling prices for memory and microprocessors could impede the industry's growth, the price war between Intel and AMD has contributed to the declining average selling price,[43] a growing number of firms are becoming dedicated design companies and outsourcing manufacturing operations to foundries because of the rising cost of conducting R&D and building fabs, and R&D is following manufacturing operations overseas. The US share of world spending on semiconductor R&D and manufacturing fell from 45% of revenue in 1998 to 11% in 2006.[44]

CHALLENGES

The US semiconductor industry is still the global leader in most respects, especially at the leading edge. However, the requirement for tremendous infusions of capital to reach the next CMOS technology node, industry globalization, and the dominance of Intel and IBM and a few other major players at the leading technology edge, have accelerated the industry's evolution from a vertically integrated industry to an industry of distributed functions, specialization and collaboration. The market barriers to operating at the leading edge path are prohibitive except to the industry titans. Improving performance through scaling will continue to be important, but improving performance by other means and tailored product-focused solutions that are quick to market are gaining importance. The major challenge for the US semiconductor industry is to maintain leadership in CMOS scaling while broadening strategy to win the race to the next transistor switch, develop a multi-disciplinary, cooperative structure that positions the US industrial base to capitalize on nanotechnology, and expand presence in the high-value custom-solution market space (SoC, SiP). The challenge for government is to set the conditions for industry success with a spectrum of initiatives ranging from investment in basic science to the fostering of conditions for increased government and industry collaboration.

Historically, worldwide demand for increasingly faster and cheaper semiconductors has remained unabated, and analysts forecast a continued strong demand across consumer, commercial, and defense domains. Over the last 40 years, the semiconductor industry has religiously adhered to two primary tenets, based on scaling, to meet the demand for higher performance. These tenets have significantly influenced or determined almost every business and technical decision of the industry, and it is hard to overstate their importance. In 1965, Gordon Moore, of Intel, observed that the surface area of a transistor as etched on an IC was being reduced by 50% every 18 months. As a result, computers were doubling in both data capacity and processing power in the same time period while the cost per function was halved.[45] This is now known as Moore's Law. Alternatively stated, the cost of producing ICs remains nearly constant and performance increases as transistors or other components are made smaller and packed more densely on the surface of a silicon chip. Equally important but less well known is Dennard's scaling law. Robert Dennard from IBM determined that power consumption is proportional to the area of the transistor. This means that even as the number of devices on a chip increased, the total power required remained constant for a given surface area. Dennard also determined that as ICs shrink they can be operated at higher speeds.[46] These "laws" are not true laws of physics and are not assured of continued applicability. In fact, scaling has a natural physical limit as quantum mechanics overtakes classical physics, and realizing the benefits of scaling—increased computing performance at lower cost, is becoming more and more difficult to achieve. As a result, the industry has a voracious appetite for sustained innovation thus stressing the "virtuous cycle" in which profit derived from the current technology node is used to fund research and development toward the next technology node. Significant expenditures by industry and government are required to educate new intellectual talent, perform research and development, develop new manufacturing processes and equipment, design new circuits and upgrade physical plants to remain on the leading technology edge.

Three factors leading to a 10% decline in the US market share over last decade can be linked to globalization: the accelerating shift of resource endowments across economies, which "flattens" the competitive landscape; shrinking technology lifecycles which cause the economic benefits of new technologies to dissipate more quickly from innovating economies; and the rise of multinational corporations.[47,48] The most competitive semiconductor companies have "gone global," distributing business units and functions that leverage the comparative advantages of multiple nations while simultaneously taking advantage of globally competitive tax laws, regulations, and foreign subsidies and skills.[49] Other companies either followed suit or dropped out of the race, leaving the titans to dominate the bulk of the industry.[50] These titans distribute wealth and technology globally, which may further level the playing field and contribute to a long-term decline in US competitiveness. According to Greg Tassey, senior economist at the National Institute of Standards and Technology (NIST), "The off shoring of a majority of state-of-the-art manufacturing capacity has offered other countries not only production technology experience but created domestic demand for scientists and engineers, some of whom are now participating in their economies' R&D efforts."[51]

Nevertheless, the requirement to maintain technology leadership from a national security perspective is essential for many reasons. This issue is discussed in more detail in the following Industry Issues section of the paper. The race to the next switch or post-CMOS technology is included in the technology leadership challenge.

The challenge at the sub-leading edge appears significantly more difficult for the US since the US does not appear to have a leadership position in this segment. As other countries have noted the critical importance of an indigenous semiconductor industry to national security, they have deliberately developed strategies to establish, grow and protect their industries but also have built an industrial base where the market barriers to entry are low. In this market segment, focused government support, specialization, and collaboration have emerged to form an alternate strategy that produces results without overcoming high market barriers at the leading edge. In this model, performance parameters such as speed-to-market, function integration, low power consumption, and strong customer focus are more important than high-end performance. In innovation theory, these alternative performance requirements lead to low-end disruptive innovation which creates new markets or reshapes existing markets and targets overshot customers with a lower-cost business model.

From our observations, US efforts at collaboration have focused on research to support performance increase through scaling rather than on product development to push the boundaries of other performance parameters. The challenge of a more competitive environment at the sub-leading edge became apparent on the international travel segment of our study. Foreign competitors with significant assistance from their foreign governments are aggressively pursuing a global leadership position in this segment through low-end disruptive innovation. As globalization accelerates diffusion of human capital, IP and technology, agile foreign companies are capitalizing on product-focused, consumer-driven demand.

Taiwan presents a compelling example where government and industry have collaborated effectively. It has established the Taiwan Industrial Technology Research Institute (ITRI), a multi-disciplinary research cluster with a four-fold focus to: (1) expand the effort on frontier technology research, (2) create business opportunities through IP deployment and new ventures, (3) develop knowledge-intensive service industries, and (4) pursue international collaboration. The research is split evenly between government and industry. ITRI has core labs (electronics, biomedical engineering, energy and environment, etc.) surrounded by product development centers (photovoltaics, medical devices, etc.) and cross-disciplinary development centers (creativity, nanotechnology, standards, etc.). The proliferation of this construct, particularly in Asia, presents a distinct challenge to US technology leadership. This type of government-supported, multi-discipline, multi-functional, collaborative approach is precisely the approach needed to stake out a leadership position in the nanotechnology environment of the future. The only similar construct we have observed in the US is the cross-disciplinary research performed at Stanford University. SRI International is leveraging a cross-discipline approach but does not move beyond the research phase.

OUTLOOK

We expect the semiconductor industry will continue to evolve as performance by other means gains importance relative to scaling. Globalization, specialization, collaboration, and distributed functions will become the norm. Consumer demand for new products with integrated functionality will continue to push the market toward rapid product development. Because of consumer location and favorable financial incentives available offshore, global distribution of the value chain and R&D capability will continue. The capital requirements will also continue to rise thus furthering the concentration of the leading edge technology in the hands of a very few.

The US industry will continue to travel the Moore's Law path to improve performance of individual ICs because it is still economically and technologically significant. However, the future of the CMOS microprocessor space will be defined more and more by the use of parallel processing as shown by introduction of two core processor products from Intel and nine core processor products from IBM. Multiple processor cores are starting to drive more of the economics of the industry versus clock speed.[52] The skills to produce such chips are another factor that will force the manufacture of microprocessors to those foundries that can afford the technology. The growth of multi-core processor products will open a niche for software companies to develop algorithms optimized for this environment.

Companies that have internal sources of cash flow for new development have an advantage over those who rely on the securities or debt market for capital. However, even the titans will increasingly seek partnerships to reduce development costs. For example, IBM has partners to spread and defray the cost of R&D.[53] IBM's chip design and manufacturing supports their bigger strategy to support the sale of information and business services.[54] IBM's semiconductor division strategy is to provide a range of foundry services for customers, to drive up utilization rates, while still providing chips that provide the backbone of systems deployed to meet customers' needs in IBM's' larger services market. IBM exploits its integrated design and manufacturing capability to build chips that the foundry-only companies cannot.[55]

Other than the titans, the industry will continue to reduce marginal costs by outsourcing device manufacturing to mega-foundries such as TSMC and SMIC. The strength of the fabless model is the avoidance of huge capital investment associated with upgrading a fab, coupled with associated operating and maintenance costs.[56] Additionally, the fabless model avoids under-utilization of manufacturing capacity resulting in higher profit margins over companies with in-house fabs. The fabless model allows companies to focus on core competencies--research, design and development--with low barriers to entry.[57]

The consequence of the fabless semiconductor model is that manufacturing is migrating to the lowest cost locations like Taiwan, Singapore and China. TSMC is the leader in the foundry space. TSMC is 10 times the size of its nearest competitor and has built its dominating position through excellent customer service and near leading edge technology. The trend in the foundry space is that more capacity is being added at such a rate that it will drive the profit margins to near zero in the future.

Another result of the distributed, fabless model is to place an increasing premium on human capital. In the distributed environment, the place to add high value shifts to the design phase which is more human resource dependent. Foreign companies are increasingly aggressive about recruiting new graduates from American universities and expatriates with extensive experience. The best and brightest minds, the real "game changers," will be highly sought in the global market without regard to nationality.

Equipment suppliers will have to change their business model. As industry leaps technology nodes every 18 to 24 months, equipment must also evolve. In the current business model, equipment manufacturers must provide the upfront capital for product development. However, as the overall industry consolidates at the leading edge leaving a dwindling market, equipment makers will have to develop joint ventures with chip makers to fund the development costs for new products. It is likely that the equipment sector will see consolidation as well.

Vulnerability to Disruptive Innovation

Even though the industry is constantly developing new technologies, the focus is generally on sustaining innovation, or how to bring better products into established markets. At the high performance end, the barriers to new market entrants are not only high but growing higher to the point that only a few oligopolies exist. At the low end the industry is almost in a state of perfect competition. The industry is ripe for disruptive innovation to occur—in the short term through custom products, and in the longer term by advances in nanotechnology Disruptive innovation occurs when companies focus on marginal improvements to sustain existing products for the most demanding customers at the expense of low-end customers or un-served markets.

Consider that customers want mobile devices with various integrated features. Customers will soon demand custom products because they don't want to pay for features they don't use. This is a niche where integration and flexibility has more value than ultimate performance. However, the titans do not have the flexibility in their processes to quickly produce custom system-on-chips because they are optimized for high-end production. Dell revolutionized the PC market because they were able to produce custom products on demand. Innovative design houses and reconfigurable foundries may soon disrupt the current industry. The demand for customization and flexibility could be met by field programmable gate arrays that are uniquely configurable based on software inputs at the expense of some high performance.

However, innovation in the emerging field of nanotechnology has far greater potential to disrupt the semiconductor industry. The opportunity to exploit nanotechnology for new products is causing a convergence of disciplines such as biology, chemistry, electrical engineering, material science, physics and diverse applied disciplines such as medicine, agriculture, and electronics. At this time, the semiconductor industry appears too tightly focused on how nanotechnology can produce better ICs and is not looking to broaden the base to encompass more semiconductor based products such as micromachines, solar cells, and flexible displays.

Clustering is the Future

As discussed in previous sections, clusters, research parks, and joint ventures will produce the most important innovations in the future. Clustering is important for basic research as well as focused product development. Not only are these collaborative efforts a response to the high costs of new development but are also necessary for knowledge fusion and cross-disciplinary research required to develop consumer products based on nanotechnology.

OUTLOOK

Technology Leadership

The semiconductor industry is critical to America for at least three reasons: (1) it has been an engine of growth for the US economy, accounting for the second largest share of exports (behind aerospace),[58] (2) the industry boosts productivity across industries and around the globe through the information technology and business process transformation it enables, and (3) it provides a dominant technological advantage to US defense forces. The US has been the "first mover" in every major technology to appear in the world economy since World War II (semiconductors, computers, software, advanced materials, network communications, and biotechnology),[59] and has reaped the rewards. Today, the US economy accounts for 25% of world gross domestic product (GDP) and is twice as large as the economy of its closest competitor, China.[60]

The mechanism by which technology leads to prosperity is two-pronged. First, high-tech products command broad global market share and high profits; second, technology applied to industry boosts productivity and output. The high-tech sector of the US economy directly accounts for 7.0% of US GDP,[61] and has bolstered the US position in international markets, maintaining an almost equal balance of trade while exports of all other goods have declined to produce a trade deficit of over $800B.[62] At the same time, technology applied to manufacturing and knowledge generation has accelerated US productivity. The productivity advantage of the US over other countries accounts for *75% of the per capita income gap*, and this productivity advantage, largely gained in the 1990s, was almost entirely due to technology investments that provided four times the rate of return as other investments.[63]

Today, the US economy is particularly reliant on the semiconductor industry. Often called "the crude oil of the information age,[64]" semiconductors enable the powerful computers and global knowledge networks that advance technology at an exponential rate and accelerate productivity in industries that produce high-demand products.[65]

Public Policy

Given that leadership in the semiconductor industry is critical to America's economic future and national defense, it is important to develop cogent and effective public policy. There appears to be a cognitive dissonance between the acknowledgement of the economic importance of the industry and the lack of coordinated policy to spur innovation, sufficiently support R&D, provide sufficient tax and other financial incentives to keep more capability onshore, and protect defense-related technologies while fostering an open global market. As a result of our site visits and discussions with many industry leaders, we learned that chip makers have moved foundry capability offshore not because of inexpensive labor but because they generally benefited from tax or other direct financial incentives by host governments. With the notable exceptions of Intel and IBM, American companies are becoming fab-less or fab-lite. It is too late for the country to address this loss, but it is not too late to retain R&D. A recent report by Dewey & LeBoeuf *Maintaining America's Competitive Edge: Government Policies Affecting Semiconductor*

Industry R&D and Manufacturing Activity, states that the share of global R&D spending outside of the US by US semiconductor companies has increased from 14% to 22% over the last decade.[66] They also note that there is a strong correlation between government incentives with the location of R&D spending.[67] Federal, state and local governments should support the development of public-private partnerships in this sector similar to the Albany Nanotechnology Research Center.

Effective public policy is also required in the area of export control. Lax controls on exported electronic technology could lead to significant advantages for our nation's adversaries. Overly strict controls could unnecessarily hamper much-needed innovation and commerce in the electronics industry. Perhaps this situation is best articulated in these words from the executive summary of the National Academies' report, *Beyond "Fortress America": National Security Controls on Science and Technology in a Globalized World,*

> As a nation, we cannot, and should not abandon well-conceived efforts to keep dangerous technology and scientific know-how out of the hands of those who would use this knowledge to create weapons of mass destruction and other, equally dangerous military systems. However, these represent a very narrow and limited set of goods, technology, and knowledge. Our former unilateral strategy of containment and isolation of our adversaries is, under current conditions, a self-destructive strategy for obsolescence and declining economic competitiveness.

Finally, US immigration policy reform is needed. Foreign nationals comprise 50% of the master's degree candidates and 71% of the PhD candidates in engineering fields relevant to the semiconductor industry.[68] The number of US educated graduates able to obtain green cards and the number of foreign nationals with requisite scientific and engineering skills able to obtain H-1B visas is limited. These limitations not only restrict the ability of American companies to take advantage of the best minds available to innovate but create a talent pool for our foreign competitors.

Research and Development

US leadership in semiconductors depends to a large extent on R&D investments, but unfortunately, these investments are becoming increasingly inadequate to maintain the competitive edge.

The Semiconductor Research Corporation (SRC) analyzed the funding required to evolve semiconductor technology to progressive nodes using the International Technology Roadmap for Semiconductors (ITRS) as a technology baseline. Performance by scaling is a large factor in determining the content and timeframe of the roadmap. SRC's study focused on the next seven to 15 years. The study identified over 200 technical challenges divided among 10 science areas, and estimated the cost of meeting these challenges at $4.6B per year. The estimate was more than twice the estimate the SRC developed in 2003 for the same task, and reflects the fact that technical problems have proven to be tougher to solve than expected.[69] Unfortunately, worldwide funding for semiconductor research is projected to be only half of the $4.6B required. This shortfall is not a crisis, but it will lead to expanding time gaps between nodes.

Total US investments in R&D have been increasing steadily by about 2.5% per year,[70] and account for over 35% of global R&D expenditures.[71] However, a better indicator of research efficacy is R&D intensity, which measures R&D expenditures as a percentage of total economic activity (GDP). Foreign countries are learning from America's success, and their economies are becoming more R&D intensive. The US currently ranks 7th in the world in R&D intensity and would have to increase R&D funding to 4.5% GDP to recapture the lead.[72] The obvious implication is that the US should increase R&D expenditures; however, it will have to do so gradually to allow R&D infrastructure to keep pace.

How and where R&D money is spent is at least as important as how much money is spent. Approximately $340B is spent in the US each year on R&D. Industry spends the vast preponderance of its R&D resources on technology development to bring products to market, while government invests in basic research and research infrastructure. In 2006, industry devoted only 4.0% of its total R&D budget to basic research, compared to 40% for the federal government.[73] As a result, total national investments were skewed, with 18% dedicated to basic research, 22% to applied research, and 60% to development.[74] The imbalance was even more acute in the computer and electronics sector (which includes the semiconductor industry) where companies and other non-federal sources funded almost the entire $43.5B R&D effort—the largest of any sector.[75] As a consequence, relatively little basic research was done in the electronics sector.

A second problem with the imbalance between public and private R&D investment, particularly in the electronics sector, focuses again on globalization. Government invests heavily in technology infrastructure, including laboratories, universities, research and development centers, and organizations that develop the infratechnologies (such as standards and measurements) that underpin the technology enterprise.[76] These investments are largely non-transferable, and contribute to long-term US competitive advantage. Industry, on the other hand, is driven by its responsibility to shareholders to invest R&D where it can generate the highest return on investment, and increasingly this is overseas. Larger portions of R&D investments by semiconductor industry titans, including breakthrough research efforts, are occurring outside the US economy.[77] Of the new R&D sites planned for construction in the next three years by the 177 leading semiconductor companies, 77% will be built in China or India, often using US corporate financing.[78]

A Human Resources Conundrum

One of the most perplexing and critical issues, we have dealt with in the course of this study is that of human capital because there is a wealth of opinions and data to support any given point of view. A construct we have found useful to frame this issue is anchored by the concept that US industry and the Defense establishment need the best and brightest human resources available to maintain a leadership position. Therefore, the US should develop and provide resources for an integrated strategy to grow, attract, and retain top talent. It is important to distinguish between the strategy for industry and DoD.

Is there a shortage of high technology workers in the US? Shortage advocates either point to the number of job vacancies reported by high technology firms or to the very low unemployment rates typically experienced in the industry. While these may seem to be good indicators of the *supply* of qualified workers, a better indicator of the *demand* for qualified workers is wage trends. Labor markets follow the basic rule of supply and demand; as the supply of workers begins to fall and job positions go unfilled, companies must raise wages to compete for the same number of workers. A cursory look at salary data would indicate that there is no shortage of engineers or scientists with graduate degrees in any Science, Technology, Engineering, Mathematics (STEM) fields of employment.[79] However, there is a large population of foreign nationals with advanced degrees that are meeting the demand for industry. There is a potential shortage of qualified workers if these foreign nationals are not retained. Anecdotal evidence suggests that there is a shortage of qualified workers to meet DoD demand, where the talent pool is smaller since foreign nationals can not work on many DoD-related projects. The US needs to establish a better human capital position.

Excellence in discovery, and innovation in science and engineering (S&E), is derived in part from an ample and well educated workforce – skilled practitioners with two- and four-year and graduate degrees. To grow this workforce requires a long-term strategy. Our education system and culture need to produce three results; an inquiring and innovative mind that enters the S&E field as a "calling;" a salary structure that provides sufficient "reward" to warrant the long slog through the education system to obtain an advanced degree, and a level of respect and appreciation for scientists and engineers that has diminished since the race to the moon in the '60s inspired a generation.

It is evident from recent reports that American K-12 education in math and science needs improvement.[80] That is the place to start. In contrast, American universities are the envy of the world for producing graduates with advanced degrees. Unfortunately, data from the Engineering Workforce Commission of the American Association of Engineering Societies show that US students represent 90% of students at American universities obtaining BS degrees in engineering but represent only 30% of the population seeking a PhD. It appears that US students weigh the opportunity costs of obtaining advanced degrees and determine that the financial or intangible rewards are insufficient. It is important to nurture and provide challenging opportunities for STEM workers that would work in those fields regardless of compensation.

Since the place to add high value shifts to the more human-dependent design phase in the distributed value chain, foreign companies are increasingly aggressive about recruiting new graduates from American universities and expatriates with extensive experience in American industry. The best and brightest minds, the real "game changers," will be highly sought in the global market without regard to nationality. As part of a retainment policy, the U.S. needs to expand the number H-1B visas allowing foreign knowledge workers to remain in America. We need a more flexible immigration policy that meets the need that isn't tied to a magic number. More importantly, we need to make the process to go from student, to visa-holder to green card holder, to citizenship much more direct and smooth to retain the best foreign human capital.

A Secure Supply Chain for DoD

The DoD has a significant challenge in crafting a policy to address the need for a secure supply chain for semiconductor-based products essential to maintaining national security. Significant effort over the last few years has been put into crafting policy to address the challenge. Directive-Type Memorandum (DTM) 08-048, "Supply Chain Risk Management (SCRM) to Improve the Integrity of Components Used in DoD Systems, establishes a policy for managing supply chain risk. The '09 Defense Authorization Act directs the DoD to perform a vulnerability assessment of the supply chain. An update to acquisition policy in DoDI 5200 addresses the issue of Critical Program Information, particularly as it applies to ASICs. As we have grappled with the secure supply chain issue during the course of the industry study, it has become apparent that it is multi-dimensional and not susceptible to a simplistic solution.

As a result of DoD policy to procure commercial ICs in lieu of custom ICs fabricated with rigid military specifications, there is little self-contained government infrastructure to make ICs. Since defense requirements represent less than 1% of the market, DoD influence and leverage within the semiconductor industry is minimal. Today, a significant portion of ICs used in the military's equipment and weapon systems come from overseas manufacturers and component resellers. The US has limited visibility of and influence over semiconductor manufacturing processes and sources of supply that ensure mission essential semiconductor devices have not been tampered with, copied, or remarked for resale. In testimony to the House Armed Services Subcommittee for Terrorism, Unconventional Threats and Capabilities Dr. Brian Cohen, Assistant Director, Information Technology and Systems Division at the Institute for Defense Analysis identified the following national security concerns: theft of important IP such as algorithms encoded as part of the chip design; tampering with IC function thereby potentially causing defense systems to be ineffective, unavailable, or to allow unauthorized access; and denial of access to advanced technologies and supplies, resulting in only older ICs being available for defense use."[81]

DoD has three categories of IC requirements: 1) commodity ICs that go in commercially available products such as those used in PCs, mobile devices or network circuit boards; 2) custom ICs for the most technically advanced applications or leading edge research; 3) commercial or custom ICs that go in weapon systems or critical infrastructure. There is a continuum of products in this category between commercial ICs and critical, custom ICs. DoD can meet the first category requirement through diligent use of direct buys from Original Equipment Manufacturers (OEM)s or their authorized distributors. The trusted foundry program was established to meet the second category requirements. We have heard repeatedly from companies participating in the trusted foundry program that they need more volume to be profitable. The requirements in this category will never be large enough to establish high volume. The original agreement with IBM leveraged excess capacity within the fabrication plant, and guaranteed IBM roughly $60 million in sales each year, regardless whether or not the government actually requested the full amount. Other US semiconductor manufacturers were encouraged to apply for certification in an effort to increase capacity and obtain access to trusted components several generations behind current technology levels. Working with the Trusted Agent Program Office (TAPO), DoD has designated the Defense MicroElectronics Activity (DMEA) as the accrediting authority, and has increased the trusted supplier base to 21 companies capable of providing varying stages of the manufacturing process in a trusted environment.[82] For many reasons, one of which is certainly increased program costs incurred by using trusted ICs in system design, not all eligible government acquisition programs are identifying and tagging critical components for inclusion in the trusted foundry program. As a result, the government is not able to maximize benefits under the terms of the contract, and the smaller accredited firms are beginning to grow impatient holding capacity in the hope that DoD will increase demand. However these requirements are so critical to national security that we will have to pay a high price for access to leading edge technology and keep these vendors in the program.

The third category of DoD requirements is the most problematic. It is further broken down into current production and sustainment. Consider ICs that are going into the most advanced weapons systems such as the revolutionary F-22. These ICs are likely to be multiple generations away from the leading edge. The technology value is at the sub-system, box level, not necessarily at the chip level. A recent DoD directive requires all ASICs to be fabricated in a trusted foundry.[83] This broad mandate is an unnecessary drag on the acquisition programs. From a Program Manager's point of view, this looks like an unfunded mandate similar to the RF tagging mandate that was never funded or enforced. Trusted foundries will be viewed as directed sub-contractors by defense contractors. This has significant cost and liability implications. Not all ASICs are critically important to the performance of the weapon system. These factors will drive systems engineers to avoid ASICs in favor commercially available products or Field Programmable Gate Arrays which can be secured through software. Engineers will avoid using designs that require use of the trusted foundry except where absolutely necessary. This means that the volume of ICs through those foundries will continue to be low. It is important to follow through with the vulnerability assessment to better establish the true requirements.

Now consider the sustainment requirement. DoD weapon systems are increasingly extended in service far past their design life; i.e., the B-52 bomber and KC-135 tanker. Therefore, the logistics supply chain must be able to obtain replacements for parts that are decades old. Because of the long life of these weapon systems, semiconductor devices that were high-tech, state-of-the-art at the time of purchase become quickly outdated in the rapidly changing, high volume commercial sector. Similarly, as acquisition timelines grow longer, some systems designed with state-of-the-art IC specifications may not be fabricated until five to 10 years after initial design. As we have seen, the business model for commercial IC facilities requires rapid technology upgrades in order to remain competitive. So there is a significant discontinuity between the majority of DoD requirements and commercial products available. Therefore, a secure method to obtain obsolete parts, or parts not quite at the leading edge, must be found to satisfy DoD needs. Commercial industry will not want to produce ICs for weapon systems that remain in the inventory for decades and government entities such as the DMEA cannot currently produce the volume of products required. A possible solution is to expand the capability of DMEA and establish an arsenal equivalent for ICs.

Export Control

The nation is concerned about the export of electronic technology that provides a competitive advantage. The US makes a distinction between goods and technologies that are dual-use and those intended for military purposes only. This distinction determines the regulatory agency in the federal government with responsibility in that arena. The Department of Commerce regulates the export and re-export of most commercial items; the Department of State is responsible for military exports.

The nation is also rightly concerned about protecting only goods and services that leave the country via exports. The US also tries to prevent certain purchases of American technology maintained onshore. Recent legislation, the Foreign Investment and National Security Act of 2007 (FINSA) was written to address this issue. The National Research Council recently released a report on the nation's security controls overseeing research in science and technology. The committee's report highlights the importance of the judicious exercise of export controls. The first two categories of recommendations regard reforming the export control process and ensuring scientific and technological competitiveness.[84] The first recommendation was that, "The President should restructure the export control process within the federal government so that the balancing of interests can be achieved more efficiently and harm can be prevented to the nation's security and technology base; in addition to promoting US economic competitiveness."[85] The committee does not recommend eliminating export controls. Rather, they suggest the appropriate governmental agencies acknowledge the interdependence between national security concerns and economic competitiveness as they make decisions on requests for licenses to export sensitive materials. Specifically, they recommend allowing, "openness and engagement to prevail unless a compelling case can be made for restrictions."[86] In other words, the committee encourages the government to give the "benefit of the doubt" to allowing commerce to take place unhindered. The committee reiterates this notion when it suggests the President should, "Create an economic competitiveness exemption that eliminates export controls on dual-use technologies where they, or their functional equivalents, are available without restriction in open markets outside the US."[87]

Intellectual Property Rights

Intellectual property rights (IPR) in the semiconductor industry have gained enhanced significance due to the increasing capability to reverse engineer and counterfeit modern ICs. Violations of IPR leading to the supply of inexpensively produced IC counterfeits in the modern marketplace create the same economic detriment to legitimate manufacturers as more classic forms of patent infringement did in the past. The World Customs Organization estimates the problem of IPR violation in the area of counterfeit computer chips alone may be costing US semiconductor manufacturers almost $8.5B each year, and the global semiconductor industry as a whole almost $17.5B each year. The enormous amount of lost sales revenue is recognized as a growing problem and the US semiconductor industry is becoming much more aggressive in defending IPR associated with IC design and manufacture. Perhaps the most common and increasingly used method to defend IPR is legal action in both national and international venues by the IPR owner against those they accuse of patent infringement. Historically, patent infringement has been more common in emerging market countries with limited capability, and some contend inclination, to enforce patent regulations. These trouble-spot countries include "China which accounts for nearly two-thirds of counterfeit goods"[88]…and other hot spots such as "the Philippines, Vietnam, Russia, Ukraine, Brazil, Pakistan, and Paraguay."[89]

With the majority of patent infringement incidents currently originating in China, the question becomes how to most effectively and constructively engage with this country to increase patent enforcement. "Some trade hawks in the US call for a World Trade Organization action against China related to counterfeits and IPR violations in general. Such pressure is beginning to have some effect. The Chinese government is starting to take IP more seriously because of the unprecedented uniform shouting coming from the US, Europe, and Japan."[90] This pressure has resulted in substantive improvements in Chinese IPR protection. In addition to IPR enforcement, a significant area for improvement is in the area of damage awards. A recent report on IPR issues in China states, "Though intellectual property rights (IPR) infringement damage awards continue to be small in China, the number of IPR awards appears to be increasing and foreign firms seem to be faring better in Chinese courts than Chinese firms."[91] The report also states, "Continued progress in the imposition of economic damages in intellectual property rights cases is likely to be in China's best interest as research and development continues to become more important to the economy."[92]

This situation constitutes a challenge to the future profitability of the US semiconductor industry that is being addressed through both US Government involvement as well as increased corporate responsibility. A combination of US government and international community pressure, coupled with increased aggressiveness on the part of US semiconductor corporations defending their IPR, has resulted in significant IPR legal protection and policy improvements within China. However, legal and political methods are inadequate to fully protect IPR. Individual companies operating in China and other emerging market countries subject to lax IPR protection must do a better job of assuming individual responsibility and implementing procedures to limit the opportunities for theft or exploitation of their IPR.

Observations on Asia

Success in the semiconductor industry does not depend on natural resources or geographic location of the country. Access to and nurturing of the sophisticated knowledge, skills, and technologies and a favorable business climate are the keys. Asian firms have benefited from a globalized world economy and a vast export market. Asian governments have aggressively engaged in activities that encourage and guide technological advances, set policies and programs that sponsor research parks, recruit overseas nationals, and coordinate technology adoption and adaptation.

With the formation of the TSMC and UMC, Taiwan became a strong player in the foundry business. Both companies continue to develop leading-edge process technologies, and have became the dominant fabrication source for fabless start-ups worldwide. Taiwan's success is due to the combination of a supportive government with a significant foreign reserve, a highly educated talent pool, and a strong entrepreneurial atmosphere.

China has successfully employed the same business model that enabled Taiwan's success for the foundry, assembly and test, and electronic manufacturing suppliers (EMS) sectors of the value chain. China is becoming a major supplier and the world's largest and most sought-after market. However, China still faces several challenges: limited production capability to meet domestic demand, poor R&D capabilities for manufacturing processes, lack of design expertise, and dependence on imports of manufacturing equipment. Innovation in China is in the field of product assembly instead of in equipment improvement innovation or new design innovation. China's strength is the ability to mass produce large quantities for quick delivery. The supply chain inside the borders is very efficient to deliver any product within about three days.

Singapore started with testing, assembly and packaging operations in the 1960s and 1970s based almost entirely on multinational corporations. These companies originally located in Singapore for cheap labor and stable working environment, but have remained while upgrading scope and depth of their technologies. Singapore's Economic Development Board (EDB) has carefully overseen and coordinated the development of its semiconductor industry, and invested in core capabilities of local industry clusters and supported the establishment of wafer-fabrication parks. The chip fabrication and test and assembly industry has flourished. Singapore's strategy has been to attract multinational offshoots, and to transfer skills and technologies across to local training, R&D institutes, and homegrown operations.

Following Singapore's success in building its semiconductor industry, Malaysia has moved in the same overall directions but has lagged a few years. Malaysia has succeeded in the backend processes including assembly and test and EMS, but not in foundry-based production. By the late 1990s, Thailand, the Philippines, and Indonesia all had made progress in the semiconductor industry by attracting multinationals in IC assembly and test operations with their low labor for low-cost manufacturing. India has established itself as the world's premier software development center within the past two decades. With a cadre of technical design experts, India has high potential to establish advanced fabs and assembly and test houses.

GOVERNMENT GOALS AND ROLE

There is urgent action required by the US Government. The critical importance of maintaining technology leadership to national security and prosperity requires a comprehensive package of policies to protect and nurture the industrial base. The semiconductor industry should be viewed as a system, with extensive integration, cooperation, and coordination required between functions, to achieve competitive goals.

Retain Top Intellectual Talent

Innovation is essential to leadership in the semiconductor industry, and PhD-level training is required to compete at the leading edge. Therefore, the US should develop and provide resources for an integrated strategy to grow, attract, and retain top talent. The strategy should address two groups: US-born American citizens and Foreign Nationals working for US companies. Targeting the first group requires a strategy to motivate graduate education in science and engineering, and should include at least three parts: (1) increased investment in STEM-related subjects in K-12 education to generate interest in technology careers, (2) expanded federal aid and grants to incentivize graduate education for US citizens completing undergraduate technical degrees, and (3) policy that allows increased financial compensation to attract and retain industry thoroughbreds. Compensation could include higher salaries and structures allowing profit and royalty sharing to reward innovation.

Foreign Nationals working in US companies are a huge source of competitive advantage and should be actively recruited and aggressively retained. In particular, the H-1B visa program should be made more flexible and reactive to meet the needs of industry and government, and the path from H-1B Visa to “green card” to US citizenship should be streamlined.

Bolster Industry Leading R&D

The US must maintain unparalleled R&D effectiveness to continue leadership in the semiconductor industry which will require strategy, direct government funding, industry incentives to promote private R&D, and government leadership to focus R&D efforts.

First and foremost, the US Government should lead an effort to establish a broad partnership with industry, universities, and other Non-governmental Organizations to execute an agreed-to technology roadmap with maximum R&D efficiency.[93] With full recognition of the new competitive landscape, government should invest in basic research that sets the foundation for the roadmap, and establish channels to rapidly diffuse generic technical knowledge throughout the domestic supply chain to enable high rates of innovation.[94] Industry, for its part, should continue to focus on bringing products to market. Government investments should bolster the national research and innovation infrastructure that confers sustained advantage on the US economy while setting the conditions that encourage multinational companies to invest R&D efforts in America.

The US Government should continue to support public-private cooperative development programs such as those at the Naval Research Laboratory, and the Nanoscience Institute at NIST. Furthermore, there is room for Federally-sponsored research in the current industry collaboration centers. State and local governments should provide financial incentive packages to develop critical technology centers of excellence such as those found at Research Triangle Park in North

Carolina and the Albany Nanotechnology Research Center in New York. The US Government should continue to support consortium efforts such as SEMATECH.

Second, government should increase direct investments in R&D from the 1.0% of GDP promised in the America Competes Act[95] to the historic high of 1.8% GDP reached in 1964.[96] At the same time, government should work with and incentivize industry to perform R&D in America with a goal of raising total national R&D investment to at least 3% GDP (near historic highs). Incentives should include, but not be limited to, a permanent R&D tax credit. Third, the US Government should exercise leadership to focus R&D efforts in areas that add significant value to the US economy and national defense. For example, the government should focus and fund efforts at the Semiconductor Research Corporation - Nanotechnology Research Initiative and elsewhere to ensure the US wins the race to the "next switch" (beyond CMOS).

Finally, the government should consider setting up something like a Federally Funded Research and Development Center (FFRDC) after Taiwan's ITRI model that incubates promising tech start-up companies and facilitates product-focused development to invigorate the economy.

Set Conditions for Industry Success within American Borders

Globalization is leveling the playing field, diffusing the basis for competitive advantage, and facilitating the rise of multi-national titans that drive large segments of the industry. Foreign governments have taken notice and are acting aggressively to capture market segments and to court the titans to locate more business within their borders. To stay competitive, the US must act to counter these increasingly powerful forces and set conditions for corporate success in America. For starters, the Government should continue deferral of taxes on income derived from offshore operating units. Congress should lower the federal corporate income tax rate to be competitive with Organisation for Economic Cooperation and Development (OECD) countries and enact a 10% investment tax credit for new investment in qualifying high technology manufacturing facilities in the US (similar to the investment tax credit that existed in federal law prior to the Tax Reform Act of 1986). Furthermore, US companies should be able to take full depreciation over three years for all semiconductor manufacturing equipment installed in US fabrication facilities. Finally, government funding and leadership in setting up world-class R&D facilities, as mentioned above, should be advertised as incentives for corporations to cluster in America.

Secure the Supply Chain

Semiconductors from trusted sources are crucial for National Defense and critical US infrastructure, and US efforts to secure trusted supplies through the Trusted Foundry Program, and the DMEA mission are laudable. However, as costs for producing ICs rise and elements of the semiconductor value chain become increasingly distributed around the globe, a second look at the strategy is warranted. The strategy for securing the supply chain should be risk-based, product-focused, and properly resourced.

First, expenditure of resources to secure the supply chain should be risk-based. The new DoD 5000.39 designates all ASICs (custom computer chips) made for defense applications as critical program information (CPI) and prescribes that they be fabricated in a trusted foundry at an increased cost. While the instruction provides a step in the right direction, it suffers by arbitrarily designating all ASICs as CPI. Depending on the application, an ASIC may in fact be non-critical while an unprotected generic part is critical. In many cases, the program manager for the product under development is in the best position to make the call.

Second, efforts to secure the supply chain should be product-focused to allow appropriate security of relevant components at the lowest possible cost. For example, leading edge, generic ICs could potentially be considered secure if they are bought directly from an OEM (e.g. Intel) while critical custom components could only be considered secure if they were manufactured and tracked through a trusted foundry. Similarly, critical obsolete parts, which incur significant risk of counterfeit, could potentially best be secured through manufacture in a government facility such as DMEA.

Finally, a comprehensive strategy to secure the supply chain must be fully resourced. One of the principal shortfalls of the new DoD Instruction 5200.39, which requires defense programs to produce all custom chips in a trusted foundry (at increased cost) is that is comes without resources, and therefore is likely to be unexecutable in many situations.

CONCLUSION

A vibrant, leading-edge semiconductor industry is essential to US national security. The industry has been an engine of growth for the US economy, the industry boosts productivity across industries and around the globe through the information technology and business process transformation it enables and provides a dominant technological advantage to US defense forces. Therefore, ICAF has performed an in-depth, but by no means exhaustive, study of the industry. In the course of the study, we observed the effect of globalization on trade, the increased requirement for capital, and the dominance of a few titans at the leading technology node, have accelerated the evolution from a vertically-integrated industry to an industry of specialization and collaboration. The industry is under increasing pressure as the time and capital required to reach the next technology node increases. As a result of the pressure, the industry is looking to achieve performance gains by means other than scaling. Speed-to-market, function integration, low power consumption, and strong customer focus are increasingly more important. Asian companies with strong foreign government support are rapidly carving out a significant piece of this segment. The US industry will continue to travel the Moore's Law path to improve performance of individual ICs because it is still economically and technologically significant. However, the future of the CMOS microprocessor space will be defined more and more by "performance by other means"--the use of parallel processing, systems on a chip, and systems in a package.

Although recent public policy changes have somewhat improved the environment, especially in regards to basic research and development, the US lacks a comprehensive and synergistic plan to fully capitalize on opportunities presented by the new environment and ensure continued leadership in a post-CMOS and multidisciplinary nanotechnology environment. The semiconductor industry should be viewed as a system, with extensive integration, cooperation, and coordination required between functions, to achieve competitive goals. We need to establish strategies to retain top intellectual talent, bolster industry-leading R&D, set conditions for industry success within American borders, and secure the supply chain for DoD requirements.

More focus needs to be placed on clustering. Clustering is important for basic research as well as focused product development. Not only are these collaborative efforts a response to the high costs of new development but are also necessary for knowledge fusion and cross-disciplinary research required to lead in the semiconductor and nanotechnology industries of the future.

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