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ABSTRACT: While currently assessed as mature and healthy, the global semiconductor industry is facing a strategic inflection point. This inflection will shape a future for the industry that is significantly different than the past. Although outlook for that future remains favorable, numerous challenges place that future at risk. Challenges found in Chinese competition, skilled workforce shortages, commercial semiconductor market shifts, unique DoD electronics needs, and ongoing requirements for rapid innovation threaten the stability of the market, the U.S. competitive advantage, and U.S. economic and national security. Future success in the industry hinges upon policies which address these challenges and enable U.S. companies to embrace future opportunities.

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Industry Study Outreach and Field Studies

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List of Acronyms and Key Terms

ASIC	Application Specific Integrated Circuit
CPU	Central Processing Unit
DARPA	Defense Advanced Research Project Agency
DLA	Defense Logistics Agency
DMEA	Defense Micro Electronics Activity
EDA	Electronic Design Automation
fab	Fabrication facility
FPGA	Field Programmable Gate Array
GIDEP	Government-Industry Data Exchange Program
IC	Integrated Circuit
IDM	Integrated Device Manufacturer
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Intellectual Property
M&A	Mergers and Acquisition
NDAA	National Defense Authorization Act
OEM	Original Equipment Manufacturer
PC	Personal Computer
PCAST	President's Council of Advisors on Science and Technology
R&D	Research and Development
SoC	System on a Chip
SIA	Semiconductor Industry Association
STEM	Science, Technology, Engineering, and Math
TSMC	Taiwan Semiconductor Manufacturing Corporation
USB	Universal Serial Bus

INTRODUCTION

Semiconductors are essential to modern life. Progress in semiconductors has opened up new frontiers for devices and services that use them, creating new businesses and industries, and bringing massive benefits to American workers and consumers as well as to the global economy. Cutting-edge semiconductor technology is also critical to defense systems and U.S. military strength, and the pervasiveness of semiconductors makes their integrity important to mitigating cybersecurity risk…Today, U.S. semiconductor innovation, competitiveness, and integrity face major challenges.[1]

This paper is the culmination of five months of extensive analysis of the semiconductor industry that the Electronics Industry Study seminar (Seminar) at the Dwight D. Eisenhower School for National Security and Resource Strategy conducted from January – May 2017. This analysis stems from intensive seminar instruction; industry, academia, and government visits in the National Capital Region; and field studies in New York, California, Taiwan, and China.

The Seminar's five-month evaluation of the industry validates the conclusions of the January 2017 President's Council of Advisors on Science and Technology (PCAST) report: the semiconductor industry is both essential to the modern American way of life and facing challenges that threaten the future success of U.S. companies in this industry. While currently assessed as mature and healthy, the global semiconductor industry is facing a strategic inflection point. This inflection will shape a future for the industry that is significantly different than the past. Although the outlook for that future remains favorable, numerous challenges put that future at risk.

The Seminar found challenges flowing from increased Chinese competition in the industry, crosscutting workforce shortages, shifts in commercial semiconductor market demand and structure, ongoing unique Department of Defense (DoD) electronics needs, and continuing requirements for rapid innovation. Combined, these challenges threaten the stability of the market and U.S. competitive advantage.

Government involvement in this industry, if implemented correctly, has the potential to support continued industry success. Policy which focuses on future, post-inflection markets and goals, rather than trying to preserve past achievements, will be the most successful. Through proactive action to address the challenges highlighted in this paper, the U.S. government can enable U.S. semiconductor companies to embrace future opportunities, ultimately preserving U.S. competitive advantage in this foundational industry, and thus preserving U.S. economic and national security.

SEMICONDUCTOR INDUSTRY DEFINED

Integrated circuits (ICs) are the core of the electronics industry. As such, the Seminar chose to concentrate its broader study of electronics into a narrower analysis of the companies that provide these critical components. The IC industry was then further subdivided into companies specializing in equipment, design, and/or manufacture of ICs, as outlined below.

Equipment: For the purposes of this study, the Seminar has designated equipment as the specific tools required to produce or test silicon wafers. This section of the industry includes companies like Applied Materials, Lam Research, and ASML. Continued development of state-of-the-art equipment is required to enable the over 600 steps required to produce leading edge ICs.

Design: The Seminar defined the design segment of the market to include the distinct market categories of design tools and fabless IC design companies. The design tool category is filled by Synopsys, Cadence, and others who provide the software and intellectual property to support the virtual design of the highly technical circuits containing billions of transistors. Companies in the fabless IC design category, such as Qualcomm and Advanced Micro Devices, then leverage these design tools to create, but not manufacture, unique designs in support of customer needs and market demand.

Manufacture: The Seminar defined the manufacturing segment of the market to include the distinct market categories of fabrication, testing, and packaging. This segment includes the traditional Integrated Device Manufactures (IDM) such as Intel and Samsung as well as foundries like Taiwan Semiconductor Manufacturing Corporation (TSMC), GlobalFoundries, or Semiconductor Manufacturing International Corporation (SMIC). The Seminar found that IDMs also possess internal design capability that could be captured within the design sector of the market as well. Finally, the manufacture segment also includes companies such as Chipmos and ASE Group that focus solely on the assembly, packaging, and testing required to produce ICs ready for Original Equipment Manufacturer (OEM) use.

The Seminar deemed it essential to evaluate each segment of the semiconductor industry separately in determining the overall health of the industry, but also noted the criticality of each segment remaining synchronized with the others. Ultimately, each segment is highly reliant on the others to produce finished ICs, and each segment must remain in tune with the others as technological advancements occur. A lag in one segment will drive repercussions that will impact all other segments across the globe.

CURRENT CONDITIONS

The global semiconductor industry continues to fuel the world's technological advances and to contribute greatly to both the global and U.S. economy. Total global revenues were $338.9 billion in 2016.[2] Additionally, the industry generated global revenue of $92.6 billion in the first quarter of 2017, an 18.1 percent increase over the first quarter of 2016.[3] The industry directly contributes over 250,000 U.S. jobs, along with indirectly creating an additional 1,000,000 jobs in the United States. Semiconductor industries and manufacturing facilities are located throughout the country, spanning 21 states, and contributing $164 billion to the U.S. economy.[4] According to the Semiconductor Industry Association, semiconductors are the fourth largest U.S. export behind aircraft, refined oil, and automobiles. The industry also reinvests heavily into research and development (R&D), contributing nearly one-fifth of annual total revenue to this cause, one of the highest percentages of any U.S. industry (See Appendix 1).

While the semiconductor industry continues to be susceptible to global economic shifts, all market leaders remain economically healthy in their respective market segments. These companies continue to provide significant value to the industry with double digit returns on investment over the past five years while simultaneously managing low levels of debt in relationship to shareholder equity, as illustrated in the solvency column of Appendix 1. Additionally, revenues have continued to rise and projections are favorable with rapid growth projected in future markets such as automotive, Internet of Things (IoT), and biomedical markets. The success of industry leaders is aided by an oligopolistic market structure in which a limited number of dominant players control substantial market share.

For all practical purposes, the great success of these market leaders, and the industry, as a whole, for the last five decades has been shaped by one man's thinking, Gordon Moore. His 1975 observation regarding component cost unexpectedly morphed into a "law"[5] which has driven the commercial semiconductor industry for decades. Intel's Moore's Law-based "Tick-Tock Model," which sought to "advance manufacturing process technology" in order to "continue to deliver the expected benefits of Moore's Law to users," highlights the traditional industry strategy.[6] Each tick cycle focused on doubling transistor density. The following tock cycle then leveraged the increased transistor density to introduce new chip architectures with improved energy efficiency, features, and performance. This clock-like pattern paced the commercial industry for years. Companies which kept pace thrived. Those who missed a beat were often left behind.

Current market conditions indicate a slowing of Moore's law with some deeming it dead.[7] Transistor density has slowed and even Intel, has acknowledged a change to market drivers with the transition from a two-year "Tick-Tock" model to a three-step "tick-tock-optimization" model for the "foreseeable future."[8] There is little dispute the pace has changed, however, and a "kind of stagnation" has entered the cycle.[9]

In addition to a changing pace, current market conditions are characterized by shifting demand. For more than a decade, personal computer, and later mobile device, unit sales have driven the global semiconductor market. For example, going back to 2004 one finds market predictions forecasting incredible 18 percent annual semiconductor market growth attributable primarily to these two products.[10] Even as recently as 2013, the International Data Corporation forecast that "semiconductors for smartphones will see healthy revenue growth as demand for increased speeds and additional features continue to drive high-end smartphone demand in developed countries and low-cost smartphones in developing countries."[11]

A significant decline in demand for both personal computers (PC) and mobile devices, however, has introduced a shift in the market. 2015 found "the outlook for the major applications that drive the semiconductor market, including PCs, smartphones, and tablets" all being revised downward.[12] Last year, *Wired* magazine declared, "[i]t's Official: The Smartphone Market Has Gone Flat."[13] Citing worldwide year-over-year growth of only 0.2 percent, the smallest on record, *Wired* declared the "era of insane smartphone growth" as "all but over."[14] At the same time, the PC industry also experienced the "biggest year-on-year decline in the history of the PC."[15] Speculation abounds as to the root cause: everyone who wants a smartphone has one, devices previously purchased are good enough to preclude the need for upgrade, etc.[16] While true, more relevant is the conclusion that market drivers have changed. PCs and mobile devices no longer drive the semiconductor market.

In addition to a changing pace and shifting demand, increased competition from overseas companies also characterize current market conditions. While the U.S. continues to lead the industry in designing the most technologically advanced semiconductors, the manufacturing, testing, and packaging aspects of the industry are increasingly overseas. This shift is due in large part to increasing cost of building/owning fabrication facilities (fabs). Upfront investment costs for leading-edge fabs is now between $5 and $10 billion. Recoupment of this massive investment requires large economies of scale—conditions which are more often found in overseas markets.

China's growing semiconductor industry also continues to be a significant factor in the global market. Large central government investment, coupled with interest and investment by local governments, is providing rapid capacity growth and increasing potential for a flooded global market. China faces an internal demand versus supply dilemma. It is currently the largest global consumer of semiconductors, but produces less than 15 percent of global wafer capacity.

Additionally, only 5 percent of those wafers China produces are at leading edge 28nm or lower processing capability.[17] To resolve this dilemma, China has implemented a "Made in China 2025" initiative which seeks to increase domestic production to 40 percent by 2020 and 70 percent by 2025. This Chinese direct investment will limit the U.S. and Taiwan's ability to compete or access the largest semiconductor market in the world—especially if the Chinese government implements trade, import, or access restrictions against foreign companies.

Finally, a "historic wave" of mergers and acquisitions (M&A), which began in 2013, continues in the commercial semiconductor industry.[18] While M&A agreements appear to have peaked in 2016 with over $116 billion in M&A agreements completed that year, even past the peak, consolidation continues.[19] SEMI, the global industry association for the micro- and nano-electronics industries, is already tracking 12 deals valued in excess of $93 billion with expected close dates in 2017.[20] This market consolidation is a force "significantly reshap[ing] the industry" with combined market share of the top ten companies expected to rise to pre-1984 levels.[21]

The U.S. government continues to rely on the semiconductor industry to fuel the technological superiority on which its economic security and national prosperity are based. However, current market conditions pose challenges to continued U.S. leadership. Intellectual property theft/manipulation, counterfeit parts, and malicious logic continue to perpetuate and propagate throughout the industry. Additionally, as foreign companies increase design capabilities, U.S. competitive advantage is declining. Direct response to these challenges is constrained because the military currently only commands 1.1 percent of semiconductor sales and the Department therefore has only a limited influence on the market. [22]

PORTER'S FIVE FORCES ANALYSIS

The Porter's Five Forces framework provides insight into the competitive forces that shape profitability and drive competition within an industry. Understanding the industry's structure is critical as firms assess their strategic positioning.

Power of Suppliers and Buyers

Fabless design firms, electronic design automation (EDA) companies, pure play foundries, equipment manufacturers, testing/packaging companies, and material providers work together to produce ICs used in finished OEM products such as mobile devices, televisions, IoT devices, and defense equipment. Since there are multiple high performing firms in the IC supply chain process, a supplier's products and services are not differentiated to the extent that it can wield substantial bargaining power over buyers. Original Equipment Manufacturers can choose substitute supplier groups with relatively low switching costs. Additionally, although market fragmentation gives supplier groups opportunities for more revenue capacity, suppliers are generally dependent upon the success of a small number of large OEMs in a highly competitive industry, which weakens supplier power. Thus, buyers can apply steady downward pressure on the price of ICs.

Within the IC production cycle, supply firms hold varying degrees of leverage. For instance, material providers of fabrication inputs such as silicon, rare earth materials, chemical manufacturing, and gas have minimum leverage due to wide availability. On the other hand, suppliers that provide unique materials process engineering capabilities, sophisticated electronic design software, or innovative semiconductor machinery manufacturing equipment remain limited in number and thus possess greater bargaining power.

Threat of Entry and Substitutes

Given the intense capital costs required to build and maintain a fab or to provide state-of-the-art fabrication equipment and materials engineering, the barriers to entry in the semiconductor industry, particularly in the IC production categories of fabrication and machine manufacturing, are high. As a result, the threat of new entrants is low. The capital required to initialize a fab is five to seven billion dollars, plus one billion dollars per year to keep up with technology. There are only three pure play foundries—TSMC, GlobalFoundries, and United Microelectronics Corporation—among the top 20 worldwide semiconductor sales leaders. Additionally, Samsung, the second-leading semiconductor company, provides foundry services, and Intel, the sales leader, fabricates its own chips. Among semiconductor equipment manufacturers, the top four companies hold over 60 percent of the global market share.[23]

For fabless design firms, the capital requirements are lower, which results in lower barriers to entry and a greater number of firms. However, among the top ten global semiconductor companies, only two are fabless design firms – Qualcomm and Broadcom. One reason it is difficult to enter the industry and sustain profitability, even for fabless design companies, is the R&D investment required to remain competitive. Semiconductor companies typically invest over 20 percent of revenue annually in R&D.

Currently, there are no imminent substitute threats to silicon-based technology. But, OEMs could threaten to switch IC fabrication providers at relatively low cost which enhances the rivalry among the handful of pure play foundries.

Rivalry Among Existing Competitors

The rapid growth in the consumer electronics industry, including new opportunities in the automotive, IoT, artificial intelligence, and virtual/augmented reality sectors, has allowed semiconductor companies throughout all phases of the IC production cycle to prosper with sizable revenue increases. This has occurred despite significant gains in chip performance, but at relatively flat unit sales prices. One of the main reasons firms can minimize the impact of competitive rivalry and sustain profitability is through concentration. In addition to the concentration of market share for pure play foundries and equipment manufacturers described above, fabless revenue is highly concentrated—the top five companies account for 57 percent of market share, and the top ten at 73 percent. Further, the top three EDA companies consume 85 percent of market share for software design tools. [24] Mergers and acquisitions have forced smaller companies into niche areas. Even the larger companies maintain strategies to focus resources on certain product lines that are well executed while carefully avoiding competition potentially damaging to profit margins.

OUTLOOK

The near and long-term outlook for the global semiconductor market is decidedly favorable. Appendix 2 shows the steady trend of annual growth in the worldwide semiconductor market, with a significant surge in revenues in just the last year.[25] As can be seen from the chart, in earlier years the semiconductor market experienced highly cyclical periods of growth and loss. The recent expansion and diversification of applications of semiconductor technology has created many new market segments, likely stabilizing growth, resulting in fewer, or less dramatic, ‘boom or bust’ market oscillations. It is anticipated that stable growth will continue.

However, despite projections of continued future growth, given previously discussed market changes including the end of scaling, shifting demand, the rise of China/increasing globalization, and the ongoing wave of mergers and acquisitions, the Seminar assesses the industry to be facing a "strategic inflection point." Former Intel CEO Andy Grove coined the phrase, noting that a strategic inflection point is a time period during which organizations or industries must respond to disruptive change in the environment or face deterioration.[26] Strategic inflection points tend to arise after periods of long success and mark a significant shift in the strategic direction of a market or organization.[27] A key feature of strategic inflection points is the inevitability of change. Whether for good or ill, change will occur and "business as usual" cannot continue.[28]

The pace and scope of change observed in the semiconductor industry suggest the outlook for the semiconductor market, and especially for individual companies within that market, will depend heavily upon adjustments away from "business as usual," especially in response to the end of scaling, shifting markets, and increased globalization.

End of Scaling

Moving forward, future growth in the market is unlikely to be driven by Moore's Law. The dramatic increase in the cost of building new semiconductor fabs has grown nearly geometrically with the advent of each new, smaller-node process.[29] Given the soaring costs of R&D with exorbitant fab costs and the increasing complexity of physics, material and manufacturing challenges brought about by smaller node sizes, the industry must look at options beyond a continued pursuit of Moore's Law. One way to continue to increase the functionality of a chip without doubling its transistors, per Moore's Law, is to approach the chip architecture differently. The System on a Chip (SoC) concept has been one method to address this challenge, particularly in mobile devices. In SoCs, multi-level and multi-architecture chips incorporate numerous central and dedicated processors (such as Graphics Processing Units (or co-processors), communications (such as Wi-Fi and Universal Serial Bus (USB)), and memory, onto a single chip.[30] The economic benefit found in one production line that minimizes packaging and volume needs while simultaneously maximizing performance through minimized interconnections, which enhance speed and reduce power draw, is compelling.

As Field Programmable Gate Arrays (FPGAs) become ever more capable and versatile, they become a second compelling option for pursuit in the post-scaling industry. These chips allow tailored configuration by customers in support of system needs. Compared to the specificity and inflexibility of Application Specific Integrated Circuits (ASICs), the flexibility offered from FPGAs lowers the "barrier to entry" for startups and those with novel designs to get to market without the significant cost and difficult access associated with low-volume ASIC design and fab efforts.[31] The future ubiquitous availability of FPGAs and the associated test and development infrastructure will likely enable accelerated adoption and use for novel concepts and applications in the post-inflection market.

Commoditization

An increased focus on FPGAs and SOCs is an indication of one likely outcome flowing from the end of scaling—a shift towards system-level alternatives as semiconductors approach commodity status. Commodity goods, by definition, are goods which are "very similar no matter who produces them."[32] As a result, all commodities of the same grade are "priced equally, and are interchangeable"[33] Most commodities are natural products such as ores and agricultural products. There is, however, precedent for high-tech material to transform into a commodity as evidenced by the steel market of the late 19th and early 20th century. As processes for steel-making were globalized, differentiation between steel from different factories or location became more difficult. Value shifted from the steel (which as a commodity became interchangeable) to the items created with the steel.

Professor Tom Lee of Stanford University makes a compelling case that "silicon is the new steel."[34] Due to multiple "convergent trends," Professor Lee argues that silicon is undergoing a transition analogous to steel.[35] Specifically, differentiation between chips is becoming more difficult—the beginning of the path to commoditization. As differentiation between chips becomes difficult, Professor Lee predicts the action will shift from "circuits to systems."[36]

Features of the strategic inflection in the industry support an argument towards commoditization. First, as the physical limits of scaling are reached, commercial industry is facing challenges in keeping up the pace of change previously required to differentiate based on node size alone. While chip makers are pursuing other methods of differentiation (such as SOCs and FPGAs), it is unlikely that these strategies alone will achieve the levels of differentiation seen in years past. In fact, for the first time last year, the International Technology Roadmap for Semiconductors laid out an R&D strategy for the industry that was not centered on differentiation via Moore's law.[37] Called "More than Moore," the strategy recommended that instead of trying to improve chip performance alone, the industry should focus on defining the applications for which chips are needed and then develop the chips to support these applications.[38] This approach essentially treats chips as the building blocks (i.e., a commodity) to create systems—a trend that appears likely to continue.

Second, the massive Chinese investment focused on developing its semiconductor industry will likely accelerate the transition of chips from a high-tech good to a commodity item. Best estimates are that "China's starting position in its quest for semiconductor prowess is well behind that of the United States."[39] The recent PCAST report estimates all foundry companies in China are at least one-and-a-half generations behind the state of the art.[40] However, despite recommendations to "run faster" (i.e., innovate faster) in the PCAST report, China's massive investment coupled with the slowing of Moore's Law suggest the gap between Chinese capabilities and that of the rest of the world will likely begin to close.[41] As the gap closes, market saturation of similar items will grow and semiconductors will move closer to categorization as a commodity good with memory becoming the first. Logical processing semiconductors will, for a while, remain differentiated.

Shifting Markets

In just the last several years, new semiconductor-fed market segments have emerged in support of: cloud computing, autonomous vehicles and systems, advanced manufacturing robotics, wearable technologies, and the IoT, just to name a few.[42] Trends suggest the following three drivers will pace the post-inflection market:

- Automotive: Less than a decade ago, self-driving vehicles would have seemed futuristic. Today they are approaching reality. Business Insider projects nearly ten million cars with some level of self-driving features on the road by 2020.[43] The computing power required to achieve autonomy will "drive the demand for high-end chips."[44] Include chips required for semi-autonomous vehicle features such as park-assist and it is easy to see how chip demand for automotive customers is expected to exhibit the strongest average annual near-term growth of any industry sector.[45]

- Internet of Things (IoT): Adding sensors and processors to "formerly dumb technology" will allow data collection and system automation at a previously unimaginable scale.[46] Business Insider analysis projects the number of internet connected devices will more than triple by 2020.[47] Of the predicted 34 billion connected devices in 2020, traditional devices will comprise less than 10 billion.[48]
- Data Centers: Massive growth of internet connected devices will translate into a corresponding exponential increase in data collection and storage requirements. The magnitude of network connections and data associated with the IoT will "accelerate a distributed data center management approach."[49] Joe Skorupa, an analyst at Gartner, suggests organizations will be "forced to aggregate data in multiple distributed mini data centers where initial processing can occur. Relevant data will then be forwarded to a central site for additional processing."[50] This boom in mini data centers suggests data center requirements as another driver of the commercial chip market beyond the inflection.

Innovation

One constant between pre- and post-inflection markets is the role that innovation must place in driving the pace of the industry. With the lion's share of design firms and R&D situated in the United States, the U.S. semiconductor industry is well-poised to maintain a preeminent position in this aspect of the global marketplace.[51] While China is moving quickly to build an indigenous semiconductor ecosystem, the Seminar assesses they will not be able to match U.S. R&D and innovation over the long term in critical market segments.

National Security Outlook

While the overall industry faces and attempts to cope with a strategic inflection, two constant impediments to national security involvement in the semiconductor market are likely to continue: Access and pace.

Access: The major impediment to national security in the semiconductor industry is specific access and the Seminar assesses this impediment to continue, even in a post-inflection market. The DoD is a mere blip in the sales numbers of most major firms.[52] Gone are the days where the DoD could dictate the terms for cutting-edge designs, and the associated production runs, to industry. The commercial sector has out-paced the DoD and its demand for innovation and cutting-edge technologies has captured the market, making it insensitive to DoD-specific needs. National security applications must either work with small design houses and limited fabs that will do boutique designs and small volume runs, or piece together a system using commercially available designs and products. The impact of this reality in either case is less than ideal. First, national security systems will continue to have limited access for unique application design and fabrication. Second, if U.S. systems are built upon commercially available products, U.S. adversaries will have the same access and can fully reverse engineer and exploit the chips.[53]

Pace: Defense acquisition development timelines will also continue to remain an impediment to DoD involvement in the advanced-node market. The slower pace required for test, mission assurance, training, and logistics support of national security system acquisition is incongruent with the rapid pace of the semiconductor industry. Given the unique and often high-power applications for DoD semiconductor applications, the U.S. government must assess the viability of securing access to state of the art chips. In many cases, highly capable systems can be designed and fielded without leading-edge technology and processes, and made to be supportable in the future through lifetime buys of parts and "heritage process" fabs that employ measures to eliminate counterfeits in the supply chain. Although the slowdown of Moore's Law will diminish the pace at which semiconductors advance, the DoD acquisition process is still two to three times longer than the average design cycle of the most advanced chips. This continues to drive the DoD to use semiconductors that are one to two generations behind the leading-edge technology.

Despite the perceived inflection and inevitably of change across the industry, the semiconductor industry will continue to become increasingly foundational to society as myriad systems bring increased automation and electronically-delivered services that will quickly become indispensable to life as we know it. Jeopardy television gameshow champion, Ken Jennings, after his landmark loss to IBM's Watson Artificial Intelligence system, said it best, "I, for one, welcome our new computer overlords." The semiconductor industry, the engine powering these "new overlords", is thus well postured for future success.

CHALLENGES

Despite the overall industry being well postured for success beyond the strategic inflection, the Seminar found that challenges to future U.S. leadership abound. Those challenges are grouped into five primary areas: China, Workforce, Commercial Semiconductors, Innovation, and DoD Electronics. The major challenges in each of these areas are summarized below with additional details provided in the essay section found later in this document:

Increasing Chinese Competition*:* In 2014, the Chinese government announced its "National IC Fund" in which central and local governments are investing more than $150 billion into the industry to become self-sufficient and reduce imports of ICs from foreign suppliers.[54] China's industrial policies threaten to reduce the U.S. semiconductor market share, and place U.S. national and economic security at risk. (China)

Science, Technology Engineering, and Mathematics (STEM) Education and Industry Shortfalls: According to one recent estimate, while only about five percent of the U.S. workforce is employed in STEM fields, the STEM workforce accounts for more than 50 percent of the nation's sustained economic growth.[55] The United States, however, is currently not producing the quantity and quality of individuals in STEM fields needed to sustain that level of growth. According to the Programme for International Student Assessment (PISA), the United States placed 38th out of 71 countries in Math and 24th in Science.[56] Current educational policies and methods are failing to provide the necessary STEM outcomes. (Workforce)

H-1B Visa Program Limitations: The H-1B program allows companies in the United States to temporarily employ foreign workers in occupations that require the theoretical and practical application of a body of highly specialized knowledge and a bachelor's degree or higher in the specialty or its equivalent. The current law caps the program at 65,000 plus an additional exemption for up to 20,000 holding a master's or higher degree from U.S. institutions each year.[57] This cap is preventing U.S. semiconductor firms from filling many highly-specialized jobs with U.S.-trained talent. Additionally, the current cap forces many highly talented individuals to competitor firms and countries in a "reverse brain drain" each year. (Workforce)

Increasing Security and Integrity Requirements One common requirement of future market drivers, whether they be IoT, automotive, data-centers, etc., is a need for increased security and integrity. Compared to PCs and mobile devices, the impact of security breaches or design failures for future market drivers is significant. The criticality of these types of failures as it relates to autonomous vehicles is self-evident—loss of life. Similarly, IoT objects which possess "the ability to change the state of the environment around them" must be secured in a manner which ensures change is not introduced nefariously or through poor design.[58] For example, IoT devices which might adjust the flow of fluids to a patient in a hospital bed based on information about the patient's medical records, must be both secure and trusted in design.[59] Ultimately, the security and integrity requirements for market drivers beyond the inflection will be much more complex than current system requirements and are a challenge that must be addressed as a precursor to future success. (Commercial Semiconductors)

Ongoing Massive Investment Requirements for Innovation*:* Innovation is the driver of continued semiconductor industry success. Across the semiconductor industry, firms normally dedicate at least 20 percent of their annual revenue to R&D. The global semiconductor industry reported total sales of $338.9 billion in 2016, and devoted approximately $67.8 billion to industry R&D. Continued investment at these levels hinges upon sales continuing at similar levels as well as government policies generating a financial environment conducive to continued investment in these areas. (Innovation)

DoD Security Requirements currently exceed Industry Requirements: DoD requires higher security measures to prevent counterfeiting and malicious insertion of dangerous code into chip hardware/firmware/software while maintaining high standards of performance over much longer life spans than commercial users. Studies show counterfeit chips, usually from Asia, have been used in major weapons systems. The DoD Trusted Supply and Trusted Foundry Programs are DoD efforts to address the concern. However, the Trusted Foundry Program produces less than two percent of the 1.9 billion DoD chips each year.[60] The DoD requires improved secure supply chain management for all of its chips, not just in leading-edge chips and ASICs, from design to manufacture to testing. Further, DoD access to suppliers of unique chips must be maintained. (DoD Electronics)

U.S. GOVERNMENT GOALS AND POLICY RECOMMENDATIONS

Since the invention of the transistor 70 years ago, American firms have enjoyed the distinction of leading the global semiconductor industry. Many of the challenges facing the semiconductor industry, as described in the previous section, are contributing to the steady erosion of this lead. To ensure its national security, the United States must preserve a positive future for its indigenous semiconductor industry. To accomplish this, the U.S. government must pursue policies that target post-inflection realities, not pre-inflection successes. All policies should recognize the existence of a strategic inflection and acknowledge market drivers—including the end of scaling and shifting market priorities. With this in mind, the Seminar has identified the following goals and policy recommendations designed to maintain U.S. leadership in the global semiconductor industry:

Goal A (China): Preserve fair and open access to global markets

Recent data published by the Semiconductor Industry Association shows that the United States still holds the majority share of IDM and fabless market sales, but it is increasingly dependent on foreign companies for foundry and assembly/test services.[61] This fact emphasizes the value of international trade and the need for responsible trade agreements with foreign partners. With such a large pool of global customers, the United States must routinely examine existing trade restrictions, embargos, and tariffs, and closely examine their impact on the domestic and international semiconductor industry. As the world moves into an increasingly interconnected environment, the demand for bleeding edge ICs will continue to grow. Responsible trade policy will position the United States. to take full advantage of these emerging markets, and will allow the United States to shape the environment instead of reacting to it.

Recommendation A1: Vigorously pursue anti-competitive practices from China. The U.S. government must continue enforcement of, while simultaneously pressuring Chinese compliance with, international trade rules. American firms are postured to succeed in this market but only if the market is fair, open, and transparent. In addition, the U.S. government should re-energize efforts to build trade agreements in the Pacific region, either bilateral or multilateral in nature, that lay the foundation for the required fair and open markets.

Recommendation A2: Enforce rules, norms, and laws that protect intellectual property (IP), both domestically and internationally. The U.S. government must protect the IP of the U.S. semiconductor industry, consistent with global laws and norms. More importantly, it must have the resolve to enforce these rules, norms, and laws. When the U.S. government can prove that a foreign actor stole the IP of a U.S. firm, it is incumbent upon the U.S. government to bring to bear all appropriate instruments of national power to discourage and/or punish foreign offenders, be they state sponsored or private industry. Punishment on an international level could range from trade restrictions/embargos to state-sponsored sanctions.

Goal B (Workforce): Encourage and attract the next generation of industry leaders

In a market as competitive and volatile as the semiconductor industry, it is critical that the industry be led by the best and brightest. With multiple nations competing for the industry's top talent, U.S. companies must focus on training and attracting talent for today, and for generations to come. The international model for cultivating talent in the semiconductor industry is to send candidates to the United States for training and education. However, what happens after graduation is critically important to the U.S. semiconductor industry. The newly trained candidates can choose to take their training back home to their nation of origin, or they can choose to apply for an H-1B work visa and apply their critical skills within the United States. However, an emerging U.S. nationalism threatens to block applicants from bringing their talent to the U.S. marketplace. The United States must assume an aggressive role in keeping these trained professionals within its borders. Moreover, the nation must do a better job at attracting and incentivizing domestic talent. These critical occupations include scientists, engineers, and experienced industry executives, which represent a critical element of the U.S. national technology base, its economic prosperity, and its national security. Attracting, training, and retaining these national assets must remain one of America's top priorities.

Recommendation B1: Pursue tailored and targeted education reform in support of all three semiconductor industry segments. Beyond advocating increased emphasis in STEM education at the elementary and secondary levels, build education policies targeted at higher education that are tailored to specific segments within the semiconductor industry. The manufacturing, testing, and packaging segments of the semiconductor industry can benefit from encouraging more students to complete two-year degrees and certificate programs in STEM, which are less costly than four-year degrees while still highly marketable. Meanwhile, the design segments of the industry require policies that emphasize four-year and advanced degrees.

Recommendation B2: Expand and reform the H1B Visa Program. Establish a separate H-1B category with its own cap to meet the unique needs of the U.S. semiconductor industry. The cap should be reviewed and adjusted annually to ensure industry needs continue to be met. The semiconductor industry is central to the economic prosperity and national security of the United States and warrants a separate category and periodic review. Additionally, this approach will help stem the flow of talent to non-U.S. firms.

Goal C (Commercial): Incentivize continued growth in the U.S. semiconductor industry

Growth in the semiconductor industry is a multifaceted endeavor. Since the United States does not directly fund its domestic IC manufacturers, the government must find alternatives to incentivize growth and to demonstrate to its industry partners that the semiconductor industry is a national priority. In line with the December 2015 precedent of tax credits for qualified research expenses[62], a tailored combination of reductions in tax rates and tax incentives can further decrease the operations costs of U.S. semiconductor firms, allowing them to strengthen investment in R&D or modernization efforts.

Recommendation C1: Pursue corporate tax reduction coupled with focused spending targets. The U.S. government should establish realistic tax policy that will generate growth at a macro level in the U.S. semiconductor industry. At the time of this report, the current administration is considering a reduction in the corporate tax rate from 35 percent to 15 percent. Such an action is expected to stimulate investments in R&D, job creation, and expansion of the commercial sector. For such benefits to be realized, this tax reduction should be coupled with spending targets to ensure that the 20 percent tax savings are dedicated to R&D, workforce investments, or capital investments.

Recommendation C2: Provide targeted tax incentives especially centered on funds repatriation. The U.S. government should offer tax credits, or a limited reduction in the corporate tax rate, to incentivize the repatriation of funds that a U.S. company's foreign subsidiaries generate. The global nature of the semiconductor market has produced a situation in which many of the largest firms hold extreme amounts of cash overseas but are unwilling to repatriate those funds due to tax implications. Incentives to return those funds to U.S. markets can stimulate additional R&D, workforce, or capital investments. As with the previous recommendation, however, these incentives must be tied to spending targets to ensure that the repatriated funds are directed toward the specific areas of need and not simply redistributed to shareholders.

Goal D (DoD): Ensure access to trusted electronics for national security applications

National security in the 21st century hinges on a nation's ability to acquire and operate advanced weapon systems across the domains of land, sea, air, space, and cyberspace. Systems in each of these domains are increasingly reliant on ICs—specifically ICs in which a nation has full trust and confidence. Consistent with previous policy statements, the DoD must continue to ensure access in the market and to ensure the nation can trust the systems which flow from that access.

Recommendation D1: Rapidly adopt emerging "trusted" supply chain technologies and reexamine the business case of the current Trusted Foundry program **to include a detailed risk and benefit analysis**. As previously noted, the current Trusted Foundry Program produces less than two percent of the 1.9 billion DoD chips each year.[63] Advanced technologies are emerging to ensure secure "chain-of-custody" throughout the semiconductor supply chain. The DoD must rapidly adopt these technologies to ensure trust of a much higher percentage of chips in its systems, while continuing to ensure access to a variety of design-houses, foundries, and suppliers capable of producing secure and reliable semiconductors that meet often unique DoD requirements.

Recommendation D2: Leverage common security and integrity interests to strengthen national security. In a post-inflection market, there is great opportunity for DoD interests to align with the interests of other market drivers—specifically automotive and IoT customers. By partnering early with industry, government users can capitalize on commercial advances to address its technological requirements. Similarly, government can partner with industry to set standards and build regulations that will satisfy the national security needs of DoD semiconductors in parallel with the higher security/integrity demands of commercial applications (e.g., automotive and IoT systems).

Goal E (Innovation): Ensure Rapid Innovation to Maintain Competitive Distance

The competitive advantage of the U.S. semiconductor industry centers around its ability to innovate faster and more successfully than any of its competitors. To facilitate and maintain this rapid innovation, the U.S. government must continue to inspire and accelerate the innovation cycle.

Recommendation E1: Continue to incentivize research in targeted, disruptive technologies such as quantum computing. Promote R&D in moonshot[64] technologies (e.g., quantum computing) that will dramatically advance the post-inflection semiconductor industry. The government can accomplish this through continuing ongoing efforts, such as the Defense Advanced Research Projects Agency's (DARPA) prize-based competition model to spur innovation,[65] and supplementing these initiatives with tax incentives and research grants.

Recommendation E2: Continue to promote public private partnerships to accelerate the innovation cycle. Continue encouraging the establishment of public private organizations that serve as innovation incubators and accelerators (e.g., those established under the Manufacturing USA initiative).[66] The focus of these partnerships should be enabling the transition from a basic, pre-competitive research phase to marketable product.

ESSAYS ON MAJOR ISSUES

CHINA: THE RISE OF NEW COMPETITION

China is poised to reshape the landscape of the global semiconductor market over the coming decade. Driven by the growing Chinese middle class, China has risen to a 58.5 percent share of the worldwide semiconductor consumption market in 2016. That year, China's share of the global semiconductor production market was estimated at a paltry nine percent.[67] This market opportunity has been filled by the global semiconductor leaders, the United States (50 percent), South Korea (17 percent), Japan (11 percent), and Taiwan (6 percent).[68] Through the “Made in China: 2025” policy, China is concentrating heavily on developing and maintaining a robust industrial base with nearly vertical supply chain integration.[69] The Chinese intend to catch up technologically in the design, fabrication and packaging of chips of all types by 2030. In the short term, the government has set a goal of producing 70 percent of its domestic consumption by 2025.[70]

As part of this policy, in 2014, the Chinese government announced a highly ambitious, orchestrated, and well-funded program to develop its independent, domestic semiconductor industry supply chain. Known as the “National IC Fund”, Chinese central and local governments are investing more than $150 billion into the semiconductor industry in order to become self-sufficient and reduce the imports of ICs from foreign suppliers.[71] China’s industrial policies, coupled with a state-supported multi-billion-dollar fund to the industry, threatens to reduce the U.S. semiconductor market share, and place U.S. national and economic security at risk.

China is leveraging a market-based approach as it consolidates its domestic semiconductor industry. Its intent is to place hubs in focused provinces to create industrial clusters, much like Silicon Valley. Aside from the subsidies that Chinese semiconductor companies enjoy from the government, Chinese companies also have an advantage over U.S. firms in their ability to survive losses in foreign markets. Revenue generated from China's huge domestic market and subsides from the Chinese government can compensate for potential losses abroad. The Chinese firms’ principal goal is not really profit, but national economic advancement and development of military capabilities to further China’s national interests.[72]

Consolidation and funding together will not catapult the Chinese semiconductor industry into a global leader. The Chinese are still well behind in technology, IP, and human capital. As a result, they must look externally to bridge that gap. To this end, China has been scrambling to invest in and/or purchase foreign semiconductor companies and poach veterans in the industry with the promise of exorbitant salaries. China is also known to encourage more nefarious business practices such as the theft of IP.[73]

One can expect the Chinese government to apply “emphasis” on the OEMs to localize their supply chains. These OEMs may not need much convincing, though, if the domestic suppliers maintain a low-cost strategy and provide local technical support. With over 70 percent of mobile phones produced in China, and steadily increasing, the “Made in China 2025” strategy certainly seems destined to succeed. In the short term, it is likely that China's industrial policy will flood the market, especially in low end chips—which will drive down prices and could drive many established firms out of business—causing huge disruptions in the global industry.[74]

China is not the only entity to recognize the growth potential of the Chinese semiconductor market in the years ahead—nearly all the firms with which the Seminar spoke over the course of this semester made similar statements, saying that being in China is critical to the future of their company. These firms want to have access to a burgeoning Chinese middle-class consumer base, which is almost larger than the entire population of the United States.

China recognizes the desire of American companies to set up shop on their shores and strikes one-sided deals with them as the price of admission. China generally seems to favor the "joint venture" approach, where a joint corporation is formed in which China owns a controlling share and has access to the IP that is introduced in the design and manufacture of the good within China.[75] Further, when a foreign company is established in China, the Chinese government often mandates a certain number of workers be Chinese citizens, and may even go as far as to dictate which positions these people will hold within the company.[76]

While some U.S. companies seem to be enjoying market access within China, others are clamoring to receive U.S. government help in establishing themselves in the Chinese semiconductor industry. China is starting to make it more difficult for new entrants, as well as those already established, to gain market share within China. Much like the United States takes a protectionist view of the health of its industry and workforce with a skeptical eye towards Chinese intentions in this country, China is now doing the same. While the United States is calling for free market access within China and bemoaning the difficulties the Chinese government is placing on new entrants, the United States is simultaneously using the Committee on Foreign Investment in the United States to stop Chinese investment and market capture within the United States.

The U.S. government must work on the enforcement of international trade rules and norms, particularly regarding Chinese anti-competitive practices. The U.S. government must place pressure on the Chinese government to follow the international trade rules set forth by the World Trade Organization Subsidy Agreement, particularly to be transparent on the Chinese government's support to their semiconductor industry. Moreover, the U.S. government should ensure China's commitment to the U.S.-China Joint Commission on Commerce and Trade that it "operates in a fair, open, and transparent legal and regulatory environment."

The U.S. government must support the U.S. semiconductor industry's innovative efforts in order to maintain its place as the technological leader. The government should invest more on basic or pre-competitive research on semiconductor related fields to fuel and accelerate future innovations that would benefit the government, industry, and academia. This leadership position must be safeguarded against Chinese attempts to obtain U.S. IP through illicit channels.

The United States needs a strong, robust domestic semiconductor industry that continues to lead the world in innovation. Consistent with this view, the PCAST report regarding the semiconductor industry, suggests that the U.S. response to China must be for the United States to "run faster".[77] The United States must out-innovate, continue to push the technology envelope, and be the first to market in every sub-industry of semiconductors that it can.

WORKFORCE: THE FUEL DRIVING INDUSTRY SUCCESS

Innovation is the engine that spurs growth of the U.S. economy. The workforce is the fuel that feeds this continuing innovation. Therefore, a qualified workforce must be available to support this ongoing growth. This is especially important for the United States to maintain its competitive advantage in microelectronics. To facilitate and maintain this competitive advantage, the U.S. must address the issues in STEM education. The United States must improve and continue to develop policies that promote both the attraction of students and qualified teachers into STEM fields. Moreover, immigration policies must be addressed in order to retain the foreign students who complete STEM degrees at U.S. colleges and universities, most notably the ones that complete masters and doctoral degrees. All STEM graduates fuel the semiconductor industry, but the advanced degree graduates are especially critical.

The U.S. semiconductor industry is currently facing ever increasing competition from other countries, especially China. The number of firms that are now going fabless in China is challenging U.S. leadership in the global semiconductor industry. The number of fabless design firms are continuing to increase and have grown from 583 in 2013 to 715 in 2015.[78] Other issues of notable concern are the development of supercomputing and quantum computing platforms that are exceeding or competing with U.S. platforms. Human capital is becoming an ever-important part of the equation for the United States to maintain its lead in design and innovation. In order to address the human capital challenge, STEM education initiatives and focused immigration policies are critical to developing and retaining the talent in the United States.

According to the most recent PISA scores from 2015, in math and science literacy and other key skills among 15-year-olds in developed and developing countries, the United States placed 38th out of 71 countries in math and 24th in science.[79] Among the 35 members of the Organization for Economic Cooperation and Development, which sponsors the PISA initiative, the United States ranked 30th in math and 19th in science. This performance is significantly below the performance of other industrialized countries especially Singapore, China, Japan, and Taiwan. To reverse this trend and incentivize students to pursue STEM-related degrees and provide qualified teachers, a partnership to address the situation must be firmly established between federal and state governments. Students and parents must be reached at an early age in an effort to stimulate their interest in STEM. In addition, there must be increased efforts at the state and local levels to provide for mentoring students, as well as to promote science and technology through fairs, events, and demonstrations. Similarly, continued industry involvement and promotion of these events are essential to further mentor and provide visible role models for STEM students. To effectively recruit at the different education levels and create an interest in STEM, companies like Micron and Qualcomm are administering internship/co-op programs and are partnering with local community colleges and grade schools on STEM initiatives. One type of incentive can be in the form of financial benefits that allow for the deduction of educational costs or student loan forgiveness for those students pursuing a STEM curriculum or obtaining a degree. There must also be financial incentives to obtain and retain qualified teachers in the form of increased pay or stipends for those teaching STEM courses or curriculums. Since industry must also be a key participant in STEM programs, there should be tax deductions for costs associated with facilitating these STEM efforts.

The other issue that the United States must address is the immigration process. The current law limits the number of foreign nationals to 65,000 who may be provided H-1B status each fiscal year. Laws further exempt up to 20,000 foreign nationals holding a master's or higher degree from U.S. universities from the cap on H-1B visas. Semiconductor industry leaders are leaning heavily on this program to fill the growing gap in their STEM jobs within the United States. The number of graduates with bachelor degrees in STEM related fields is relatively balanced between native born at 43.4 percent and foreign born at 37.4 percent; however, it is more skewed at the advanced degree level with 22.3 percent being native born and 49.3 percent foreign born. The biggest concern is the loss of these advanced degreed graduates that are so critical to fill the jobs in design that fuel the innovation in the U.S. semiconductor industry or that fill STEM faculty positions at the university level that educate the next generation. The unemployment rate of only 2.8 percent (third quarter 2016) in the semiconductor industry is well below the overall unemployment rate of 4.5 percent and is a direct indicator of how challenging it is to fill jobs in the semiconductor industry. American policies should establish a new exemption category on H-1B visas for the semiconductor industry while providing a path forward for those graduates with advanced degrees to obtain either a green card to allow for permanent residency or, at a minimum, eliminate the time limit for an H-1B visa in order to provide a bridge to obtaining permanent residency.

DOD ELECTRONICS: MEETING SECURITY NEEDS

"Military applications were the primary driver for the invention of semiconductors,"[80] but they are no longer. The DoD historically "supported research on semiconductors and was an early key customer of the new technology."[81] The DoD used to lead the chip market, but today, while commercial industry uses billions of chips, the DoD purchases fewer than one percent of the chips sold each year. That limits economies of scale for purchase and production. The DoD is a less attractive customer to the semiconductor industry due to the limitations related to security, trusted firms, and the nature of the desired equipment between the commercial customer and the DoD. However, chips are at the heart of DoD platforms (e.g., the F-35 contains thousands of chips) and the DoD needs chips that it can trust and purchase efficiently.

The DoD has high security and performance requirements, sometimes requiring chips manufactured to much higher specifications than commercial industry, and is more risk averse than the commercial industry. The DoD must protect its systems from counterfeit chips or maliciously inserted code in hardware, firmware, or software. With some chips containing billions of transistors, chips are so complex that it is impossible to verify the design, hardware, firmware, and software of each chip. As a result, some nefarious actors use counterfeit chips, or even insert malicious hardware or software into chips, in order to make a profit, or to harm buyers. (See Appendices 3 and 4 for recent examples of counterfeit chips). "At every state of the manufacturing process, an adversary can maliciously alter the chip."[82] Counterfeits and malicious insertion are a concern for any chip, but especially for logic chips. Most of the DoD's logic chips are FPGAs[83], but some are ASICs. The DoD might consider implementing acquisition rules that require standardization of FPGAs across its defense systems. FPGAs can cost hundreds to hundreds of thousands of dollars; ASICs can cost millions.[84] In fact, the F-35 program tried to stop using ASICs due to lifecycle and supportability issues.[85]

Because its programs may last decades, chips for DoD programs need to last for long periods of time, and replacement chips for DoD programs may be decades old. Unlike the commercial market, the danger to DoD acquisitions is increased because in many DoD acquisitions, "approximately 70 percent of electronics in a weapons system are obsolete or no longer in production prior to system fielding."[86] Because of the longevity of DoD programs, the Defense Logistics Agency (DLA) may not stock parts in inventory and relies on others to obtain obsolete parts.[87] The "DoD can contact after-market firms specializing in discontinued parts (e.g., Rochester Electronics, which manufactures obsolete parts) or it may tap in-house government production capabilities. But it is often cheaper and faster to acquire the discontinued part from an outside contractor."[88] Unfortunately, the need for old chips increases the opportunity for counterfeiters to disrupt the supply chain.

Several reports in recent years have comprehensively analyzed the problems facing the DoD and recommended solutions. See Appendix 5 for a summary of the key reports and Appendix 6 for a summary of some government action to date. The DoD has recognized the challenges associated with chips, and has taken steps to increase security and reliability. Specifically, it implemented the Trusted Program in 2004 to increase trust in chips; it mandated increased supply chain management accountability; and it commissions R&D to combat counterfeits and malicious insertion.

The DoD created the Trusted Foundry Program in 2004 to produce some of the ASICs in key programs, by some accounts, less than 2% of the total number of chips purchased by DoD each year.[89] The current Trusted Foundry Program contract with Global Foundries expires in 2023. The purpose of the program is outlined in DoD Instruction (DoDI) 5200.44, "Protection of Mission Critical Functions" and requires: "[i]n applicable systems, integrated circuit-related products and services shall be procured from a trusted supplier accredited by the Defense Microelectronics Activity (DMEA) when they are custom-designed, custom-manufactured, or tailored for a specific DoD military end use,"[90] that is, in ASICs. However, the trusted program accounts for only a small number of the chips that the DoD uses, and the foundry program only produces ASICs, not the many FPGAs that the DoD buys. The return on investment for continuing the Trusted Foundry program will quickly diminish as the DoD pushes for 14nm technology in its next acquisition programs. Additionally, the complexity of the chip design, mask development and processes to manufacture leading edge chips reduces the ability to introduce malicious changes into the design or fabrication of the chip.

The DoD requires secure supply chain management for all of its chips, including for leading edge chips. Changes to DoD regulations in recent years have improved the requirements for secure supply chain management, and increased penalties on contractors who provide bad chips. DoDI 5200.44 paragraph 4c(2) addresses supply chain management, and paragraph 4c(3) requires suppliers "to detect the occurrence of, reduce the likelihood of, and mitigate the consequences of unknowingly using products containing counterfeit components or malicious functions."[91] The 2012 National Defense Authorization Act (NDAA) required assessment, policies and action regarding counterfeit parts, including chips. It requires suppliers to use the Government-Industry Data Exchange Program (GIDEP), and permits the DoD to withhold payment for counterfeit chips.[92] The GIDEP is a DoD program where government and industry exchange information about counterfeit chips. Unfortunately, reporting to GIDEP is lacking.[93] The 2012 NDAA also required regulations addressing "contractor responsibilities for detecting and avoiding the use or inclusion of counterfeit electronic parts … and requirements for contractors to report counterfeit electronic parts and suspect counterfeit electronic parts."[94]

The DoD must learn to adapt to the speed of semiconductor technological change. It currently supports R&D into combatting counterfeit chips and malicious insertion, and in examining the future of chips. Organizations like DARPA have developed potential solutions to counterfeiting, such as using chip fingerprints,[95] or dielets inserted on chips. See Appendix 7 for DARPA programs. Having embedded technology in the chip at manufacture that allows backwards accountability to determine the production source of the chip will provide additional security.

The DoD has recognized the current chip challenges, and has taken steps to address those concerns. However, more needs to be done to address the Trusted Program and foundry access, improve supply chain management, and improve security of legacy and leading-edge chips in the DoD inventory.

INNOVATION: PERPETUAL ADVANCEMENT REQUIRED

Semiconductors are a critical and fundamental technology that is at the core of all electronic devices across the commercial and national security spectrum, including dual-use, defense, intelligence, special operations, cyber, and combat mission applications.[96] The semiconductor industry is volatile, highly competitive, and global. As noted previously, a driving factor behind the highly dynamic, rapidly changing nature of the industry is Moore's Law—specifically, the need to continue realizing a doubling of semiconductor capability on an 18-24 month cycle, despite a deceleration in this rate due to physical limitations of the chip. This innovation imperative results in firms across the industry normally investing at least 20 percent of their annual revenue in R&D to maintain their competitive advantage.[97]

The very ubiquity of this technology makes semiconductors an indispensable commodity[98] used to spur innovation, and ultimately, prosperity for the United States. Simultaneously, semiconductors are such a fundamental and critical technology upon which the nation's security rests, that the United States must concern itself with ensuring a secure and constant supply. Implicit within the concern over supply chain integrity is also an imperative to ensure the quality of the technology is sufficiently advanced to meet the requirements of the U.S. government and to drive further innovation. The inherent dual-use nature of semiconductors presents a unique challenge to the U.S. security apparatus in that there is a need to allow, if not encourage, the spread and adoption of the technology within the United States to fuel innovation in related industries and end use technologies or systems (e.g., IoT, robotics, quantum computing, weapons systems, communications networks) while simultaneously preserving and protecting the nation's competitive advantage in the global semiconductor industry.

One of the most prominent factors for spurring innovation is a society's tolerance of failure and creativity. This factor ties directly to a question regarding whether some cultures may be more inclined toward true innovation than others. Acknowledging that innovation is the lifeblood of multiple emerging and critical technologies, several industry leaders have identified differences in the societal and cultural attributes of nations that promote innovation versus those that stifle it. One industry executive noted that creativity is an innate trait that can be found in people around the world. However, certain nations do a better job than others at fostering this creativity, while other nations have a more rigid institutional structure that suppresses it. Specifically, he noted that Americans not only celebrate mavericks with brilliant ideas, Americans are far more results-oriented, and accepting of novel or risky concepts—regardless of who was the originator. By contrast, this executive noted that other, less innovative nations were often more focused on the affiliation or past performance record of the inventor. Along these lines, true innovation can only occur through trial and error. Thus, the culture, and its acceptance of failure, creativity, and innovation have a direct impact on a nation's learning efficiency and educational structure, which in turn impact the nation's ability to absorb technology and innovate.

Innovation clusters[99] can be critical force multipliers. Silicon Valley in the San Francisco Bay region is the preeminent industrial center within the semiconductor industry. It is a textbook example of the benefits that accrue when complementary industries are geographically collocated so that they can forge couplings that enable the spread of concepts and realizing the benefits of shared advancements to create new technologies. The long history of innovation within Silicon Valley, which is synonymous with advances in the semiconductor industry, stands testament to the ability of the U.S. industry to not only absorb, but truly create the most advanced technological concepts within the semiconductor field. The U.S. government sponsored Manufacturing USA institutes are another example of collaborations among academia, industry, and government designed to promote the pre-competitive research that fuels industrial innovation. Conversely, the Chinese government's policy to support its indigenous semiconductor industry is far more direct. In 2014, the PRC published the "National Guideline for the Development and Promotion of the IC Industry," that, among other things, established an investment fund to stimulate the semiconductor industry with approximately $150 billion, and outlined production targets that amount to an increase from around 10 percent to 70 percent of the global market share by 2025.[100] The U.S. methodology centers around stimulating growth through encouraging innovation while the Chinese efforts are far more direct in terms of both investment and policies that could negatively impact foreign competitors.

A specific example of how national governments spur innovation is through targeting key, disruptive technologies that will enable collaboration within the triple helix of government, industry, and academia. One of the most important fields for innovation in the electronics industry on which the U.S. government must focus is quantum computing. In 2015, the U.S. still outspent all other countries with respect to quantum computing – but it is not enough. This revolutionary technology requires significantly more investment: quantum computing will be critical in the information age. The collection, exploitation, processing, and distribution of data will only take on increased importance over the coming decades. Industry is less incentivized to invest in quantum computing, and quantum encryption/decryption technology will be key for secure communications over the next 50 years. China is hurtling towards the quantum era placing bets on the disruptive and revolutionary potential of quantum technology.[101] China is already ahead in the race for quantum cryptology with almost twice as many patents as the United States.[102] China's current quantum programs reflect a whole of government approach that the U.S. government, with its inconsistent funding, cannot match. Instability in the level and consistency of R&D funding from the U.S. government has hindered significant progress in the quantum information sciences.[103] The United States cannot allow itself to fall behind in these critical, emerging technologies.

While the U.S. has historically been the innovator and leader in the global semiconductor industry, China is steadily closing the gap. There is a simultaneous drag on the American innovative capacity due to a deceleration in Moore's Law and the resulting high R&D costs coupled with a highly competitive global semiconductor industry and Chinese policies focused on rapidly building its national semiconductor industry. The primary initiative that the United States can undertake to address these concerns is enhancing the quantity and quality of interactions that make up the core of cooperation between government, industry, and academia. This serves two purposes, first it facilitates more opportunity to "fail fast" and it ensures that the institutional setup that facilitates learning efficiencies incorporates input from government and industry—which should cement the need for and importance of such interactions going forward. The question remains as to whether the right factors exist in China to enable this type of disruptive innovation.

CONCLUSION

This paper provided an overview of the global semiconductor industry. Assessment of the industry suggests a future unlike the past. Driven by the end of scaling, rise of China, and shifting demand, the industry faces a strategic inflection. This strategic inflection provides numerous opportunities for continued industry success but also numerous challenges. Challenges related to China, workforce, commercial markets, DoD electronics, and innovation were assessed. Through proactive action to address the challenges highlighted in this paper, the U.S. government can enable industry to embrace future opportunities and ultimately preserve U.S. competitive advantage in this foundational industry.

Appendix 1

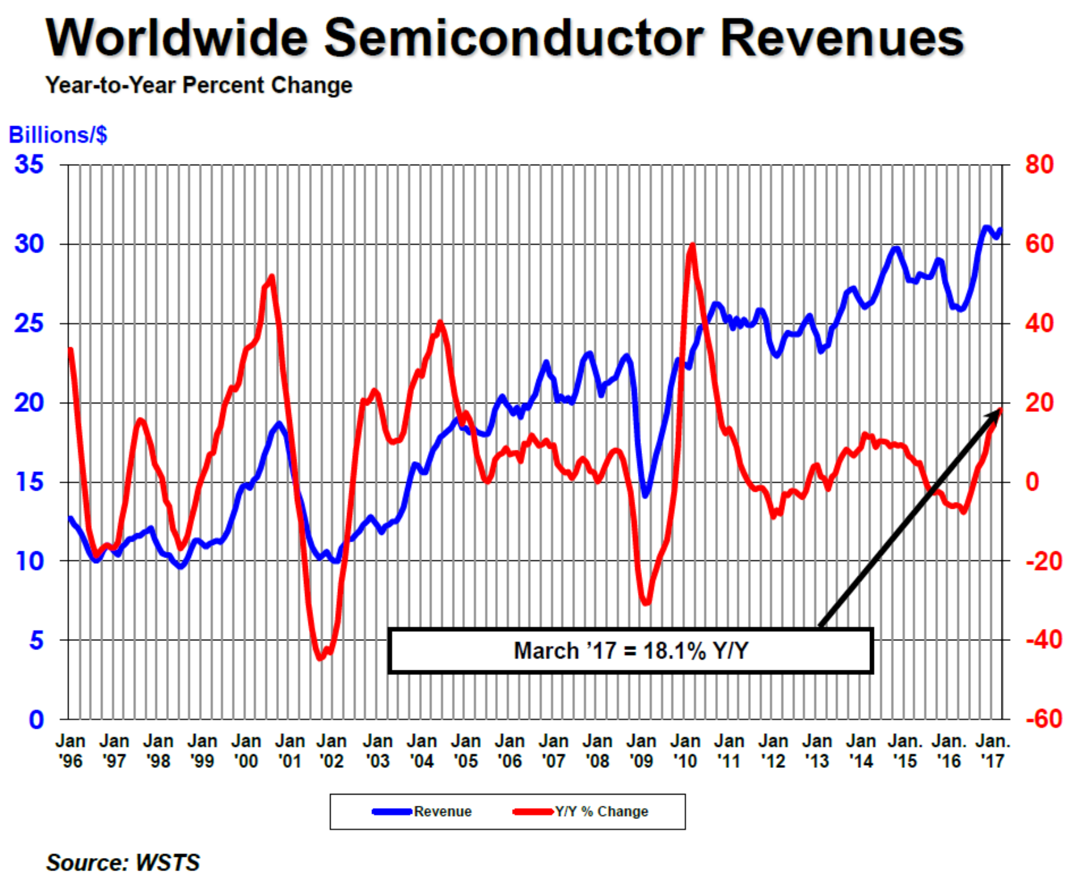
U.S. Financial Data for U.S. Semiconductor Companies

Company	Revenue 2015	Revenue 2016	% Change	Profit 2015	Profit 2016	R&D 2015	R&D 2016	Solvency	ROI 5 yr Avg	Employees
Intel (IDM)	44.36B	59.39B	25.31%	14B	12.87B	26.20%	21.50%	0.31	17.45%	106,000
Micron (IDM)	16.197B	12.399B	-30.55%	-275M	2.899B	9.50%	13%	0.76	6.79%	31,400
QualComm (Fabless)	25.3B	23.6B	-7.20%	5.7B	5.3B	22%	22%	0.32	15.24%	30,500
AMD (Fabless)	3.99B	4.27B	6.56%	-481M	-372M	23.70%	23.40%	4.25	-23.65%	8,200
Applied Materials (Equipment)	9.66B	10.83B	10.80%	1.38B	1.72B	14.20%	15%	0.44	8.35%	16,700
Cadence (Design Tools)	1.7B	1.82B	6.59%	252,417M	203,086M	37.50%	40.50%	0.87	15.24%	7,100
Synopsis (Design Tools)	2.24B	2.42B	7.44%	225,934M	266,826M	34.60%	35.40%	0.066	7.17%	3,870

Financial Data for Overseas Semiconductor Firms

Company	Revenue	Revenue	% Change	Profit 2015	Profit 2016	R&D 2015	R&D 2016	Solvency	ROI 5 yr Avg	Employees
TSMC (Foundry/Taiwan)	26.44B (2015)	29.257B (2016)	9.63%	9.24B	10.24B	8% (2014)	8% (2013)	0.11	21.86%	46,968
UMC (Foundry/China)	3.92B (2013)	4.46B (2014)	12.11%	1.008B (2014)	745.66M (2013)	10% (2014)	10% (2013)	0.039	3.34%	18,623
SMIC (Foundry/China)	2.23B (2015)	2.91B (2016)	23.37%	682M	849M	9.6 (2014)	7% (2013)	0	4.25%	13,473
Chipmos(Testing&Packaging/Taiwan)	576M (2011)	608M (2012)	5.26%	-481M (2011)	22.84M	2.3% (2011)	2.6% (2012)	0.42	9.81%	6,205
ASML (Equipment/Netherlands)	6.35B (2014)	6.82B (2015)	6.89%	1.51B	1.3B (2014)	16.99%	18.34% (2014)	0	15.05%	14,681

Appendix 2


Worldwide Semiconductor Revenues
Year-to-Year Percent Change
Billions/$
35
30
25
20
15
10
5
0
80
60
40
20
0
-20
-40
-60
March '17 = 18.1% Y/Y
Jan '96
Jan '97
Jan '98
Jan '99
Jan '00
Jan '01
Jan '02
Jan '03
Jan '04
Jan '05
Jan '06
Jan '07
Jan '08
Jan '09
Jan '10
Jan '11
Jan '12
Jan '13
Jan '14
Jan. '15
Jan. '16
Jan. '17
Revenue
Y/Y % Change
Source: WSTS

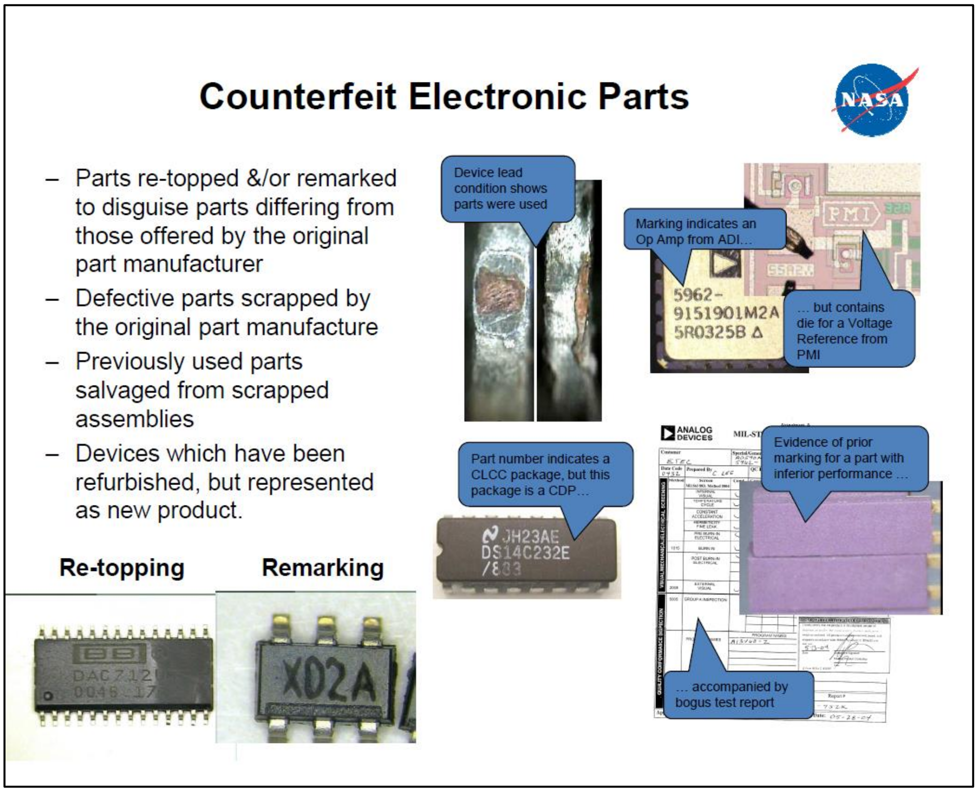
Appendix 3

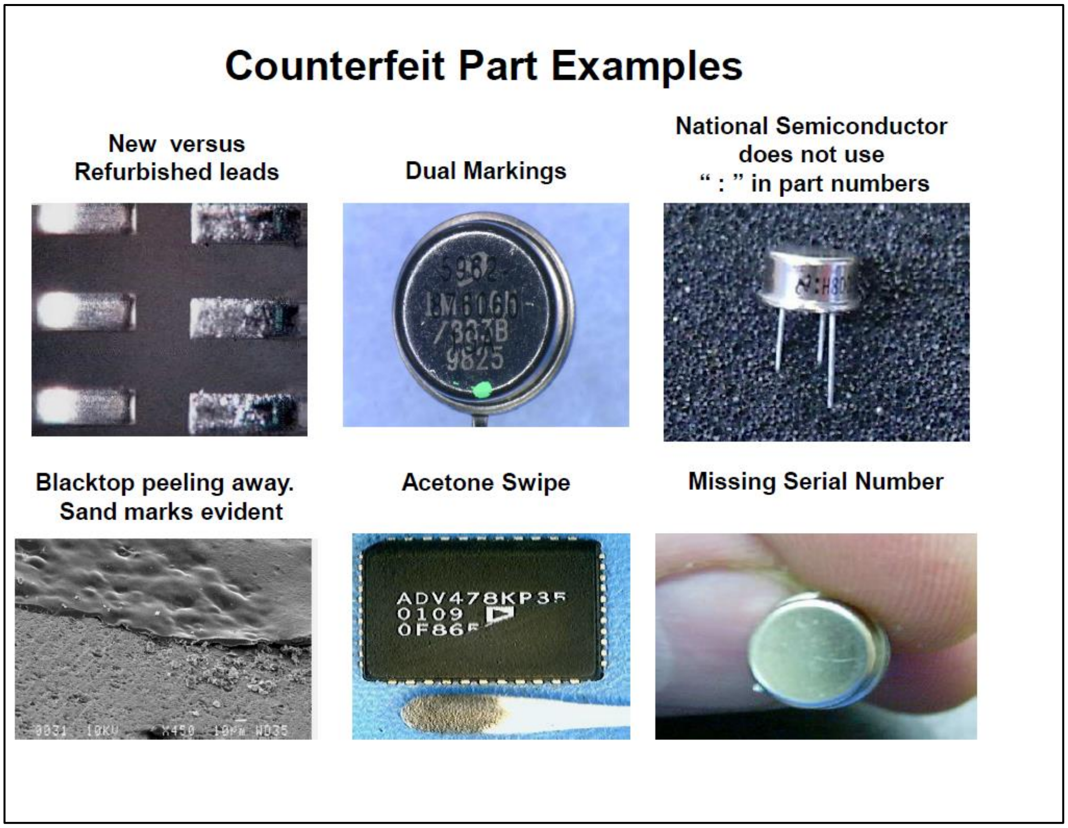
Examples of Counterfeit Chips in the Supply Chain

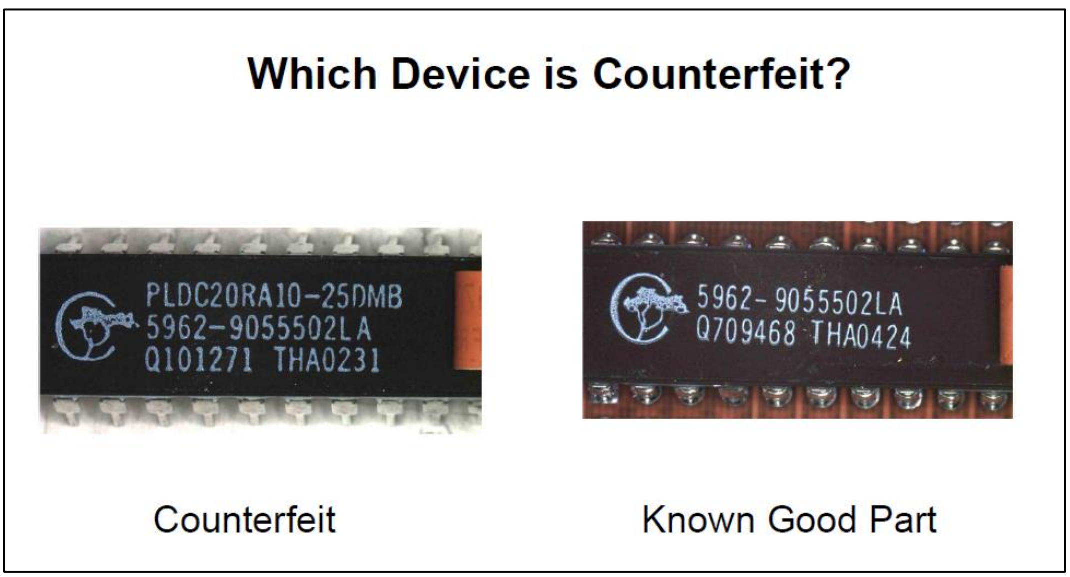
2005-2008	A significant problem prosecuted by DOJ. Counterfeits intentionally sold to DoD from 2005-2008.[104]
2005-2008	"The U.S. Department of Commerce reported a 142 percent increase in counterfeit parts between 2005 and 2008, the majority of which were commercial electronic components widely used across every major technology end-market." [105]
2011	1,300 counterfeit chips reported in 2011; DoD bought and used some of those chips.[106]
2011	"In 2011, the five most commonly counterfeited semiconductor types were analog integrated circuits (ICs), microprocessors, memory ICs, programmable logic devices, and transistors."[107]
2012	Senate Armed Services Committee report saying that counterfeit electronics from China were found in U.S. military vehicles, which included a Navy surveillance aircraft. "China is the dominant source country for counterfeit electronic parts that are infiltrating the defense supply chain," the report stated."[108] Investigation discovered counterfeit electronic parts from China in the Air Force's largest cargo plane, in assemblies intended for Special Operations helicopters, and in a Navy surveillance plane among 1 million counterfeit parts in 1,800 cases of counterfeit parts.[109]
2012	Russia initially blamed a downed spacecraft (Phobos-Grunt lander) on counterfeit chips – chips that were mislabeled as space grade, but were lower quality, probably milspec, and not tested for radiation.[110]
2012	"…the U.S. Air Force says that a single electronic parts supplier, Hong Dark Electronic Trade of Shenzhen, China, supplied approximately 84,000 suspect counterfeit electronic parts into the DoD supply chain. Parts from Hong Dark made it into Traffic Alert and Collision Avoidance Systems (TCAS) intended for the C-5AMP, C-12, and the Global Hawk. In addition, parts from Hong Dark made it into assemblies intended for the P-3, the Special Operations Force A/MH-6M, and other military equipment, like the Excalibur (an extended range artillery projectile), the Navy Integrated Submarine Imaging System, and the Army Stryker Mobile Gun."[111]
2012	The 2012 Senate report uncovered examples including thermal weapons sights delivered to the Army, on mission computers for the Missile Defense Agency's Terminal High Altitude Area Defense (THAAD) mission, and on military aircraft including SH-60B, AH-64, and CH-46 helicopters (sic) and the C-17, C-130J, C-27J, and P-8A Poseidon.[112]
2012	"The expense to resolve a single counterfeit incident can be massive. For example, the government reported how the U.S. Missile Defense Agency learned that mission computers for Terminal High Altitude Area Defense (THAAD) missiles contained suspect counterfeit devices that could have led to an entire system failure. The cost of that fix was nearly $2.7 million."[113]
2015	Arrest and prosecution of seller for selling almost 15,000 chips from 2007-2012.[114]
2015	DoD "agencies and contractors submitted 526 suspect counterfeit parts reports in the Government-Industry Data Exchange Program (GIDEP) from fiscal years 2011 through 2015, submitted primarily by contractors. Defense agencies and contractor officials explained that congressional attention to counterfeit parts in 2011 and 2012 led to increased reporting, and that the lower number of reports in more recent years is partly the result of better practices to prevent the purchase of counterfeit parts."[115]

Appendix 4

Counterfeit Parts







Source: Brian Hughitt, Presentation on “Counterfeit Electronic Parts,” NEPP Electronics Technology Workshop, June 22-24, 2010, accessed at https://nepp.nasa.gov/workshops/etw2010/talks/08_Hughitt_Counterfeit%20Electronics%20-%20All%20the%20World's%20a%20Fake.pdf on April 8, 2017.

Appendix 5

Recent Reports on Counterfeits and Malicious Insertion

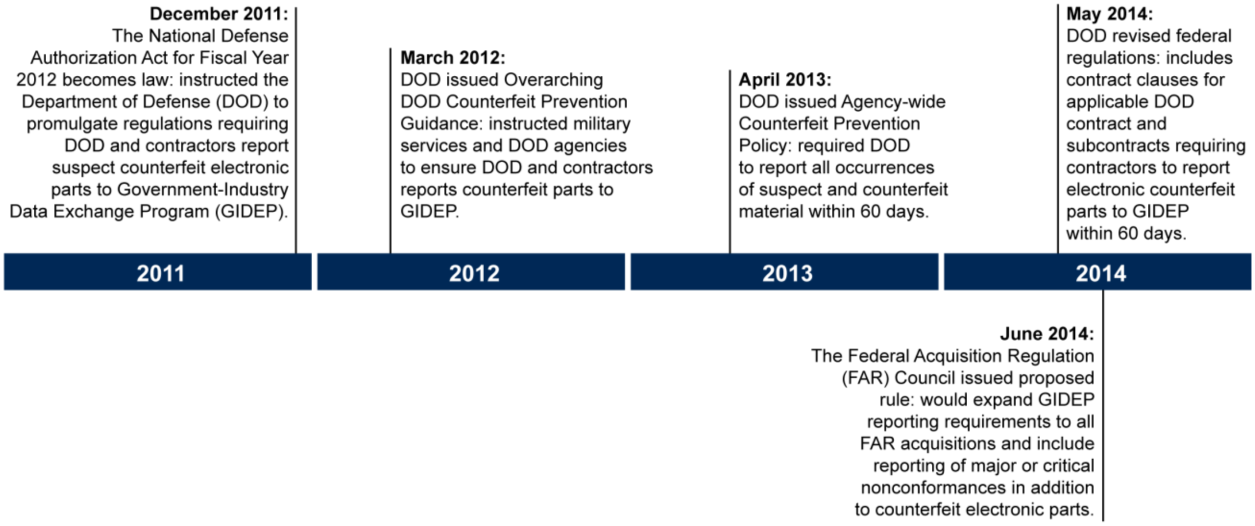
2010	NEPP Electronics Technology Workshop report on "Counterfeit Electronic Parts."[116]	It provided a detailed analysis of the problem of counterfeit chips. See Appendix B for some examples of counterfeit chips.
2012	GAO reported on "DoD Supply Chain - Suspect Counterfeit Electronic Parts Can Be Found on Internet Purchasing Platforms"[117]	A thorough report on GAO experiences. GAO advertised for replacement parts but received **no** legitimate parts in response. Instead, GAO received counterfeit parts, legitimate parts but with falsified post-production date codes, and fake parts.[118]
2012	Senate report on "Inquiry into Counterfeit Electronic Parts in the Department of Defense Supply Chain."[119]	The report found over 1,800 cases with over 1 million suspect chips.
2013	The Semiconductor Industry Association (SIA) reported on "Winning the Battle against Counterfeit Semiconductor Products."[120]	It provided another detailed analysis of the dangers of counterfeit chips.
2015	GAO testified before Congress regarding chips.	GAO noted that by 2015, the trusted program had expanded to include over 60 trusted micro-electronics suppliers, though DoD only used IBM (now Global Foundries) for fabrication of leading edge trusted microelectronics.[121]
2015	Testimony of Ms. Kristen Baldwin, Principal DASD (SE) before the House Committee on Armed Services Subcommittee on Oversight and Investigations regarding DoD microelectronics and the trusted and assured program.[122]	Overview and update on trusted and assured program.
2016	GAO released GAO 16-236, "Counterfeit Parts; DOD Needs to Improve Reporting and Oversight to Reduce Supply Chain Risk."	Recognized continuing need for supply chain improvement.
2016	CRS, "U.S. Semiconductor Manufacturing: Industry Trends, Global Competition, Federal Policy," June 27, 2016.[123]	Overview of industry. Limited applicability to counterfeit chips and malicious insertion
2017	President's Council of Advisors on Science and Technology report on "Ensuring Long-Term U.S. Leadership in Semiconductors."[124]	Interestingly, while they offer recommendation on US technology and China, among others they do not even mention counterfeits or malicious insertion or trusted foundry, or how to deal with the problem.
2017	Defense Science Board Report on Cyber Supply Chain.	25 in depth recommendations. No public examples of successful MI on DoD components.[125]

Appendix 6

Actions Taken to Combat Counterfeits and MI

Year	Action	Impact
2004	DoD and the NSA created the Trusted Foundry Program in 2004 to deal with rising threat.[126] DMEA now manages the Trusted Program.	TFP provides an increased level of trust for some chips used by DoD.
2009	DoD adopted SAE International's Aerospace Standard 5553 Counterfeit Electronic Parts: Avoidance, Detection, Mitigation and Disposition (AS5553).	Oddly, DLA, which provides almost 90% of DoD parts, does not use that standard.[127]
2012	NDAA addresses counterfeits.	Required assessment, policies and action regarding counterfeit parts, including ICs. Requires Government-Industry Date Exchange Program (IDEP) usage and reporting, and permits DoD to withhold payment for counterfeit chips.[128] The GIDEP is a DoD program where government and industry exchange information about counterfeit chips. Unfortunately, reporting to GIDEP is lacking.[129] Also required DFARS regulations to address "contractor responsibilities for detecting and avoiding the use or inclusion of counterfeit electronic parts … and requirements for contractors to report counterfeit electronic parts and suspect counterfeit electronic parts."[130]
2012	DODI 5200.44, (updated August 25, 2016), "Protection of Mission Critical Functions to Achieve Trusted Systems and Networks (TSN)."[131]	Requires trusted suppliers accredited by Defense Microelectronics Activity (DMEA) for ASICs. Para 4c(2) "Control the quality, configuration, software patch management, and security of software, firmware, hardware, and systems throughout their lifecycles, including components or subcomponents from secondary sources. Employ protections that manage risk in the supply chain for components or subcomponent products and services (e.g., integrated circuits, field programmable gate arrays (FPGA), printed circuit boards) when they are identifiable (to the supplier) as having a DoD end-use. (3) Detect the occurrence of, reduce the likelihood of, and mitigate the consequences of unknowingly using products containing counterfeit components or malicious functions…."[132]
2013	SIA's Anti-Counterfeiting Task Force's 2013 Report. Report was ratified by the <u>World Semiconductor Council</u>.	Worldwide recognition of problem and solution. Primary "recommendation was for customers to buy semiconductor products either directly from Original Component Manufacturers (OCMs, the chip companies) or their authorized distributors or resellers."[133]
2013	DoD published DODI 4140.67, "DoD Counterfeit Prevention Policy."	Policy attempted to "1) prevent the introduction of counterfeit materiel at any level of the DoD supply chain, including electronic parts; and 2) provide direction for anti-counterfeit measures for DoD weapon and information systems acquisition and sustainment to prevent the introduction of counterfeit materiel."[134]

2014	DoD issued new rules dealing with chips.	Rules required contractors to track, inspect and test chips. The rules also required contractors and their subcontractors to accepts the cost of counterfeit chips, and suffer penalties if the contractors did not "maintain acceptable safeguards" against counterfeit chips."[135]
2014	2014 regulations	Required "all technology purchased by federal government agencies to go through an approval process that checks for risks of cyberespionage or sabotage. Most importantly, the new law requires officials to look into the supply chain for technology, and bans anything with a risk to cybersecurity."[136]
2015	DoD, responding to the 2014 NDAA direction, created the Joint Federated Assurance Center (JFAC).	To "establish a joint federation of capabilities to support trusted defense system needs to ensure the security of software and hardware developed, acquired, maintained, and used by DoD."[137]
2015	Congress acted to make the R&D tax credit permanent.[138]	Federal support for R&D.
2016	Federal efforts to improve semiconductors, including Semiconductor Technology Advanced Research Network (STARnet), a partnership between DARPA and semiconductor and defense companies. Creates a network of research centers focused on "finding paths around the fundamental physical limits threatening the long-term growth of the microelectronics industry."[139]	Federal support for innovation in the semiconductor industry.
2016	JEDEC is SSO – Set new JESD243 standard.[140]	
2016	DARPA has several projects designed to ensure the integrity of chips. Each is important, but for the purposes of this paper, IRIS, TRUST and SHIELD are particularly noteworthy.	"Basing the degree of trust assigned to an IC on measurable metrics, TRUST makes a radical departure from conventional approaches."[141] See Appendix C for more information on DARPA projects.
2016	"Semiconductor manufacturers recently reached agreement on a set of requirements, practices, and methods to reduce the risk of counterfeit parts entering the supply chain."[142]	Industry further agreed on standards.
2017	US Air Force contracted for better chip analysis. "Officials of the U.S. Air Force Research Laboratory at Wright-Patterson Air Force Base in Ohio announced a $23.8 million contract to Varioscale for the Rapid Analysis of Various Emerging Nanoelectronics (RAVEN) project."	"RAVEN focuses on developing an analysis tool capable of imaging minimum-size circuit features on a silicon integrated circuit chip for process verification and failure analysis."[143]



Source: PL 112-81, § 818; Memorandum for Secretaries of the Military Departments and Directors of the Defense Agencies, Overarching DOD Counterfeit Prevention Guidance (March 16, 2012); DODI 4140.67; 79 Federal Register 26092 (May 6, 2014); 79 Federal Register 33164 (June 10, 2014). | GAO-16-236

Appendix 7

DARPA Solutions

The DARPA solution is a menu of hardware security options that can be selectively applied to tackle known security threats

	Protection	Program	CPI Theft	Fraudulent products	Loss of access	Malicious insertion	Quality & reliability
			Microelectronics Security Threats				
Strategic Foundry Partnerships	Government-proprietary	Other	●				
	Fine Disaggregation	**TIC** (IARPA): Disaggregate ASICs into non-functional parts	●	●	○	○	
	Transience	**VAPR**: Shatter lost, misplaced, or end-of-life ASICs on command	●				
Blended Partnerships	Functional Disaggregation	**SPADE**: Use secure parts to monitor commercial components packaged together into a single ASIC	●			●	●
		DAHI: Disaggregate ASICs into functional subcomponents	●		○	●	
		CHIPS: Establish a library of pre-verified, modular ASIC design IP	○		○	●	●
Commercial Manufacturing	Obscuration and Marking	**CRAFT**: Apply modularity to reduce ASIC design effort and allow portability across foundries			●		●
		eFuses: Obscure ASIC functionality until after manufacture	●			●	
		SHIELD: Authenticate ASICs at any point in the supply chain	○	●			
	Verification and Validation	**IRIS**: Derive an ASICs functionality and reliability		●		●	●
		TRUST: Reverse engineer ASICs and compare to design		○		●	

● Primary Impact
○ Secondary Impact

TIC – Trusted Integrated Chips
VAPR – Vanishing Programmable Resources
DAHI – Diverse Accessible Heterogeneous Integration
CHIPS – Common Heterogeneous Integration &IP Reuse Strategies
CRAFT – Circuit Realization at Faster Timescales
SHIELD – Supply Chain Hardware Integrity for Electronics Defense
IRIS – Integrity and Reliability of Integrated Circuits
TRUST – Trusted Integrated Circuits

Source: William Chappell, "A Technology-Enabled New Trust Approach," DARPA, accessed at http://www.darpa.mil/attachments/NDIA2.3.pdf on April 19, 2017: 12.

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