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U.S. Semiconductor Manufacturing: Industry Trends, Global Competition, Federal Policy

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Summary

Invented and pioneered in the United States shortly after World War II, semiconductors are the enabling technology of the information age. Because of semiconductors new industries have emerged and existing ones, such as aerospace and automotive, have been transformed. Semiconductors have contributed in powerful and unique ways to nearly all fields of science and engineering, and semiconductors' economic and military importance has made the industry's health a focus of congressional interest for nearly 70 years. In July 2015, Congress formed the Semiconductor Caucus, a group that seeks to advance policies that support the U.S. semiconductor industry.

The federal government played a central role in the creation of the U.S. semiconductor industry. World War II funding for electronics and materials research and development (R&D) provided essential support for the invention and refinement of semiconductors. Federal investments in computing advances also created an important application for semiconductors and federal acquisitions for defense, space, and civilian applications made up the lion's share of the early semiconductor market. In the face of formidable competition from Japanese companies in the 1980s, Congress co-funded SEMATECH, an industry research consortium devoted to developing the technologies needed by U.S. firms to remain competitive. Today, Congress continues to provide funding for R&D and development of scientific and engineering talent in support of the industry. In 2015, Congress acted to make the R&D tax credit permanent, a policy priority of the industry.

An ongoing issue of congressional interest is the retention of high-value semiconductor manufacturing in the United States. In 2015, semiconductor manufacturers directly employed 181,000 workers, who earned an average wage of $138,100, more than twice the average wage for all U.S. manufacturing workers. Increasingly, however, U.S. firms are building semiconductor fabrication plans (fabs) abroad, primarily in Asia. In addition, some semiconductor firms are going "fab-less," focusing corporate resources on chip design and relying on contract fabs abroad to manufacture their products. At year-end 2015, there were 94 advanced fabs in operation worldwide, of which 17 were in the United States, 71 in Asia (including 9 in China), and 6 in Europe. The Chinese government regards the development of a domestic, globally competitive semiconductor industry as a strategic priority with a stated goal of becoming self-sufficient in all areas of the semiconductor supply chain by 2030. China faces significant barriers to entry in this mature, capital-intensive, R&D-intensive industry.

Because the primary market for U.S.-based semiconductor firms is located outside the United States (83% in 2015), passage of the Trans-Pacific Partnership (TPP) agreement and successful conclusion of the ongoing Transatlantic Trade and Investment Partnership (TTIP) negotiations with Europe are top industry priorities. In 2015, exports of U.S. semiconductors and related devices totaled $41.8 billion, making it the nation's fourth-largest overall exporting industry. The 2015 expansion of the World Trade Organization (WTO) Information Technology Agreement (ITA), a plurilateral tariff-cutting agreement focused on trade in information technology goods, is considered a major success for the U.S. semiconductor industry.

Semiconductor manufacturing also raises national security concerns, including secure access to trusted suppliers of advanced semiconductors and other critical technology components that are important for certain defense and national security applications. The House Armed Services Subcommittee on Oversight and Investigations held a hearing on this issue in October 2015.

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Introduction

Semiconductors, tiny electronic devices based on silicon or germanium, provide data processing capabilities in millions of products, from coffee pots to space vehicles. The U.S. government played a significant role in the development of semiconductor technology, and domestic research and production have long been matters of intense congressional interest.

U.S.-headquartered semiconductor firms accounted for about half of worldwide semiconductor sales in 2015.[1] However, U.S.-headquartered producers face stiff competition from firms headquartered in South Korea, Japan, and Taiwan; moreover, the Chinese government has identified global leadership in semiconductors as a national priority. Further, the United States accounts for a diminishing share of global semiconductor production capacity, as manufacturers establish plants in locations where generous subsidies are available or customers in user industries, such as electronic products manufacturing, are nearby. In July 2015, Members of Congress concerned about the industry's competitiveness formed a Semiconductor Caucus to support increased federal funding for semiconductor research activities, among other objectives.

Semiconductor Industry Basics

A semiconductor chip (also known simply as a "semiconductor" or "chip") is a tiny electronic device (generally smaller than a postage stamp) comprised of billions of components that store, move, and process data. These functions are made possible by the unique properties of semiconducting materials, such as silicon and germanium, which allow for the precise control of the flow of electrical current.

Semiconductors are the enabling technology of the information age. Semiconductors allow computers to run software applications, such as email, Internet browsers, and word processing and spreadsheet programs and to store documents, photographs, videos, music, and other data. They also provide the "brains," memory, and data communication capabilities of countless other products, from cell phones and gaming systems to aircraft and industrial machinery to military equipment and weapons. Even many products with roots in mechanical systems are now heavily dependent on chip-based electronics: one car manufacturer asserts that some of its models incorporate as many as 6,000 semiconductors.[2] And one expert on software in cars estimates that premium-class automobiles can contain close to 100 million lines of software code (instructions) that the chips use to control the vehicle.[3]

Semiconductor History and Technological Challenges

Military applications were the primary driver for the invention of semiconductors. Early computers relied on thousands of vacuum tubes, crystal diodes, relays, resistors, and capacitors to perform simple calculations. The federal government, academia, and U.S. industry undertook

[1] Semiconductor Industry Association (SIA), "Global Semiconductor Sales Top $335 Billion in 2015," press release, February 1, 2016.

[2] Audi, "Immense Significance for Innovations: Semiconductors," http://www.audi.com/com/brand/en/vorsprung_durch_technik/content/2014/10/underrated-qualities-semiconductors.html.

[3] Robert N. Charette, "This Car Runs on Code," *IEEE Spectrum*, February 1, 2009, http://spectrum.ieee.org/transportation/systems/this-car-runs-on-code.

efforts to reduce and simplify the number of these devices. The invention of the transistor, a simple semiconductor device capable of regulating the flow of electricity, was followed by the development of the integrated circuit (IC), in 1958. ICs allowed thousands of resistors, capacitors, inductors, and transistors to be "printed" and connected on a single piece of semiconductor material, so that they functioned as a single integrated device. In addition to funding academic and industrial research that contributed to the early development of semiconductor technology, the federal government played a central role in the commercialization of the technology through purchases of semiconductors for a variety of military, space, and civilian applications.

The semiconductor industry has a rapid internal product development cycle, first described by the former CEO and co-founder of Intel Corporation, Gordon Moore. Moore's Law, which is actually an observation about the pace of development and cost reduction in chip speeds, has held true for decades. It states that the number of transistors in a dense integrated circuit will double about every 18 months to two years, making semiconductors smaller, faster, and cheaper.[4] The effects of Moore's law are evident in short product life-cycles, requiring semiconductor manufacturers to maintain high levels of research and investment spending. A main challenge for the industry is that semiconductor inventory and technology can become obsolete quickly, leaving producers with serious financial problems if they have unsalable inventories as improved designs displace existing products.

A major question facing semiconductor manufacturers is whether fundamental physical limits may soon make it difficult to pack more transistors onto a silicon device in an economical way .[5] If this proves to be the case—the continuing validity of Moore's law is hotly debated—then manufacturers would need to find other methods of improving semiconductors.[6] Research is underway into new approaches to computing (such as quantum computing, optical computing, and neuromorphic (brain-like) computing) that could, theoretically, vastly surpass the storage, processing, and transmission capabilities of semiconductor technology.[7] These approaches, however, face substantial technological obstacles to their realization.

The Global Semiconductor Industry

The semiconductor industry is generally characterized by large fluctuations in product supply and demand, depending heavily on the strength of the global economy.[8] U.S.-headquartered firms have the largest share of the global market, measured by sales, at close to 50%.[9] Half of the 20

[4] Dylan Tweney, "April 19, 1965: How Do You Like It? Moore, Moore, Moore," *Wired*, April 19, 2010, http://www.wired.com/2010/04/0419moores-law-published/; Stephen Shankland, "Moore's Law: The Rule that Really Matters in Tech," *CNet*, October 15, 2012, http://www.cnet.com/news/moores-law-the-rule-that-really-matters-in-tech/.

[5] Some features of chips are now under 10 nanometers (nm), and Intel anticipates a 5nm process in 2019. For comparison, eight hydrogen atoms side-by-side would measure about one nanometer. This size-scale presents challenges for manufacturability and adverse effects related to heat and unique quantum phenomena. Each reduction in feature size is considered a move to a new generation of manufacturing technology, and each new generation generally represents a doubling of the density of transistors on a silicon wafer, creating ever more powerful semiconductors.

[6] For differing opinions on the future prospects of silicon-based semiconductors, see "Double, Double, Toil and Trouble," *The Economist*, March 12, 2016, and Bret Swanson, *Moore's Law at 50: The Performance and Prospects of the Exponential Economy*, American Enterprise Institute, November 2015, pp. 14-15.

[7] Conceptually, quantum computing relies on quantum phenomena to expand the number of states in which data can be encoded and stored; optical computing relies on light, rather than electric current, to perform calculations; and, neuromorphic computing relies on mimicking the architecture and processing used by biological nervous systems.

[8] Angelo Zino, *Semiconductors & Semiconductor Equipment*, S&P Capital IQ, May 2016, pp. 19-24.

[9] SIA, *Factbook 2016*, April 1, 2016, p. 2.

largest semiconductor firms by revenue in 2015 are headquartered in the United States: Intel, Qualcomm, Micron, Texas Instruments, Broadcom, Apple, SanDisk, NVIDIA, Advanced Micro Devices, and On Semiconductor.[10] Other leading firms are based in South Korea, Japan, Taiwan, and Europe. There are no China-based semiconductor firms on the top 20 list.

Only a handful of companies have the sales volume to operate as integrated device manufacturers (IDMs) operating their own fabrication facilities (known as fabs).[11] Other chip firms are "fabless," meaning that they design and market semiconductors but contract production to "foundries" that manufacture semiconductors to order. Taiwan Semiconductor Manufacturing Company (TSMC), a Taiwanese-headquartered company, operates the world's largest foundry. Fabless semiconductor firms generally enjoy higher and less volatile profit margins than semiconductor manufacturers with integrated operations.[12] Potential risks associated with the use of a contract foundry include availability of capacity, timeliness of production, and quality control.

Semiconductor Industry Sales

Worldwide semiconductor sales reached $335 billion in 2015, up 15.0% over 2012, according to figures from World Semiconductor Trade Statistics (WSTS).[13] During the same period, sales of U.S.-based semiconductor manufacturers rose 14.6%. According to Semiconductor Industry Association (SIA) data, global semiconductor sales have increased at a compounded annual rate of 9.5% over the past 20 years.[14]

In recent years, semiconductor sales of U.S.-based companies have accounted for about half of worldwide semiconductor sales (see **Figure 1**). In 2015, total sales of U.S.-headquartered semiconductor firms experienced a contraction, and its global market share dropped two percentage points to 49.6%. In 2015, U.S.-headquartered firms posted sales of $166 billion.[15] WSTS forecasts a modest increase in worldwide semiconductor industry sales to $347 billion (+4%) in 2017.[16] According to semiconductor industry experts, it seems likely that the U.S. market share will remain around 50% in 2017.

[10] IHS Technology, "Global Semiconductor Market Slumps in 2015, IHS Says," press release, April 4, 2016, https://technology.ihs.com/576301/global-semiconductor-market-slumps-in-2015-ihs-says.

[11] Fabrication is the multi-step process used to create integrated circuits, including microprocessors, memory, and microcontrollers. The entire manufacturing process takes six to eight weeks and is performed in fabs that require clean rooms. Integrated device manufacturers (IDM) can also provide their chip manufacturing capacity to companies that do not have their own fabrication facilities. In some instances, IDMs lack sufficient capacity and outsource some of their chip manufacturing to contract foundries.

[12] Ulrich Naeher, Sakae Suzuki, and Bill Wiseman, *The Evolution of Business Models in a Disrupted Value Chain*, McKinsey & Company, McKinsey on Semiconductors, November 1, 2011, pp. 33-34, http://www.mckinsey.com/industries/semiconductors/our-insights.

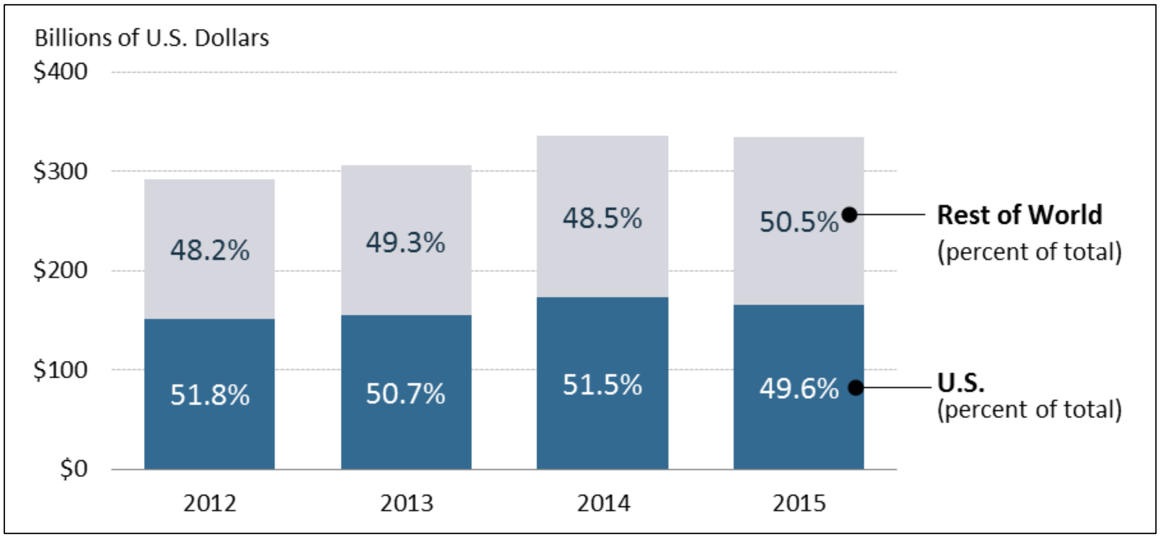
[13] World Semiconductor Trade Statistics (WSTS), "Worldwide Semiconductor Market is Expected to be Slightly Positive in 2016 and Grow Moderately in 2017," press release, February 25, 2016, https://www.wsts.org/PRESS/Recent-News-Release.

[14] SIA, *Factbook 2016*, April 1, 2016, p. 2.

[15] SIA, "Global Semiconductor Sales Top $335 Billion in 2015," press release, February 1, 2016.

[16] WSTS, "Worldwide Semiconductor Market is Expected to be Slightly Positive in 2016 and Grow Moderately in 2017," press release, February 25, 2016.

Figure 1. Worldwide and U.S. Semiconductor Industry Sales



Source: Semiconductor Industry Association (SIA), *The U.S. Semiconductor Industry, 2014, 2015, and 2016 Factbooks*.

Major Industry Segments

Semiconductors are classified into major product groups, mainly based on their function. Some of these products have broad functionality; others are designed for specific uses. According to SIA, integrated circuits, which are directly embedded onto the surface of the semiconductor chip, account for the overwhelming majority of industry sales (82% in 2015). The remaining 18% of the market is made up of sales in the optoelectronics, sensors, and discretes (O-S-D) market. Optoelectronics and sensors are mainly used for generating or sensing light, for example, in traffic lights or cameras, and discretes are used in electronic devices to control electric current.[17]

Within the integrated circuit market, the four largest segments in 2015 were:

1. **Logic Devices.** Logic devices are used for the interchange and manipulation of data in computers, communication devices, and consumer electronics.[18] Logic devices are the largest category by sales, accounting for 27% of the total semiconductor market.
2. **Memory Devices.** Memory devices store information. This segment includes dynamic random access memory (DRAM), a common and inexpensive type of memory used for the temporary storage of information in computers, and flash memory, which retains data in the absence of a power supply. Memory devices account for 23% of semiconductor market sales.
3. **Microprocessors.** Microprocessors execute software instructions to perform a wide variety of tasks such as running a word processing program or video game. They make up about 18% of semiconductor sales.
4. **Analog Devices**. Analog devices include analog signal processing technologies, data converters, amplifiers, and radio frequency integrated circuits. These

[17] SIA and Nathan Associates, *Beyond Borders: The Global Semiconductor Value Chain*, May 2017, pp. 41-42.

[18] Angelo Zino, *Industry Surveys Semiconductors & Semiconductor Equipment*, S&P Capital IQ, May 2016, p. 50.

devices, for example, convert analog signals like a musical recording on a phonograph into digital signals like a musical recording on a compact disc. Analog device products account for about 13% of semiconductor industry sales.[19]

Many manufacturers specialize in certain types of semiconductors. For example, South Korean manufacturers Samsung and SK Hynix and U.S.-based Micron together account for 90% of global DRAM sales.[20] Heavy dependence on the DRAM market has been a challenge for these companies, as weak demand or excess capacity have at times led to dramatic reductions in prices.[21] U.S.-based Intel Corporation, the largest semiconductor manufacturer by sales, is highly dependent on supplying microprocessors to the personal computer industry. Microprocessors are harder to manufacture, more technologically advanced, and more expensive than other semiconductor products, providing Intel some shelter from competition, but the company is nonetheless affected by weakening global demand for personal computers.[22]

Multicomponent semiconductors (MCOs) represent a fast-growing segment of the semiconductor industry. These devices combine two semiconductors into a single unit, which takes up less room within the finished product and use less power. MCOs are commonly used in smartphones, tablets, and automotive braking, steering, and air bag systems. Although SIA does not track sales figures for this market, the U.S. International Trade Commission (USITC) estimates that MCOs account for between 1.5% and 3.0% of global semiconductor industry sales.[23] Demand growth is expected to be high in coming years as end-use producers use MCOs to make smaller, lighter, and faster devices that consume less power. U.S.-headquartered companies such as Intel, Texas Instruments, Qualcomm, and Broadcom are among the leaders in this market segment.

A few semiconductor companies manufacture mainly for a single buyer. For example, Kokomo Semiconductors, now part of General Motors (GM) Components Holdings, operates a small fab plant in Indiana, where it produces custom integrated circuits for GM.[24] According to industry experts, small semiconductor firms can compete effectively with larger ones by producing specialized chips for particular market niches or by developing new applications for their customers.[25]

Semiconductor Manufacturing

The production of semiconductors is extremely complex, requiring high levels of automation. As semiconductors become smaller and are more densely packed with transistors, the complexity of manufacturing increases.

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[19] SIA and Nathan Associates, *Beyond Borders: The Global Semiconductor Value Chain*, May 2017, p. 41.

[20] Anne Shields, *Why DRAM Pricing is a Key Concern for Micron*, Market Realist, July 10, 2015, http://marketrealist.com/2015/07/dram-pricing-key-concern-micron/.

[21] Jeho Lee, "The Chicken Game and the Amplified Semiconductor Cycle: The Evolution of the DRAM Industry from 2006 to 2014," *Seoul Journal of Business*, vol. 21, no. 1 (June 2015), pp. 2 and 22.

[22] Intel, "Intel Announces Restructuring Initiative to Accelerate Transformation," press release, April 19, 2016, http://files.shareholder.com/downloads/INTC/1958830663x0x886662/6D73A0D5-A8CD-48A2-96E7-5234880B6304/Press_Release_Q1_2016_restructuring_-_FINAL.pdf.

[23] USITC, *The Information Technology Agreement*, Advice and Information on the Proposed Expansion: Part 2, February 2013, pp. 3-9.

[24] Kokomo Operations Overview, http://www.slideshare.net/boilerfunk/kokomo-semiconductors-introduction-sep-3-2010. Kokomo's website notes that through the years the company has broadened its customer base to include other automotive component suppliers, personal computer manufacturers, and avionics electronics suppliers.

[25] First Research, *Semiconductor & Other Electronic Component Manufacturing*, March 21, 2016.

Figure 2 depicts a simplified schematic of the semiconductor production process. The process has three distinct components:

5. design;
6. front-end fabrication, in which "fabs" create microscopic electric circuits on silicon wafers;[26] and,
7. back-end testing, assembly, and packaging, in which wafers are sliced into individual semiconductors, encased in plastic, and put through a quality-control process.

The majority of design work, performed by computer engineers, now occurs in the United States.[27] The designs are then placed on a wafer of silicon or other material in a sequence of more than 250 photographic and chemical processing steps using equipment produced by firms such as Applied Materials, ASML Holdings, and Lam Research.[28] This front-end fabrication process typically takes about 2 months.[29] Around 87% of advanced worldwide fab capacity is now located outside the United States (see **Table 1**). Back-end production is where chips are assembled into finished semiconductor components and tested for defects. This stage of the manufacturing process is the most labor-intensive and is often performed in countries such as China and Malaysia, where labor costs are lower than in the United States, Japan, and Europe. The final stage of manufacturing involves the installation of the chips into consumer goods.

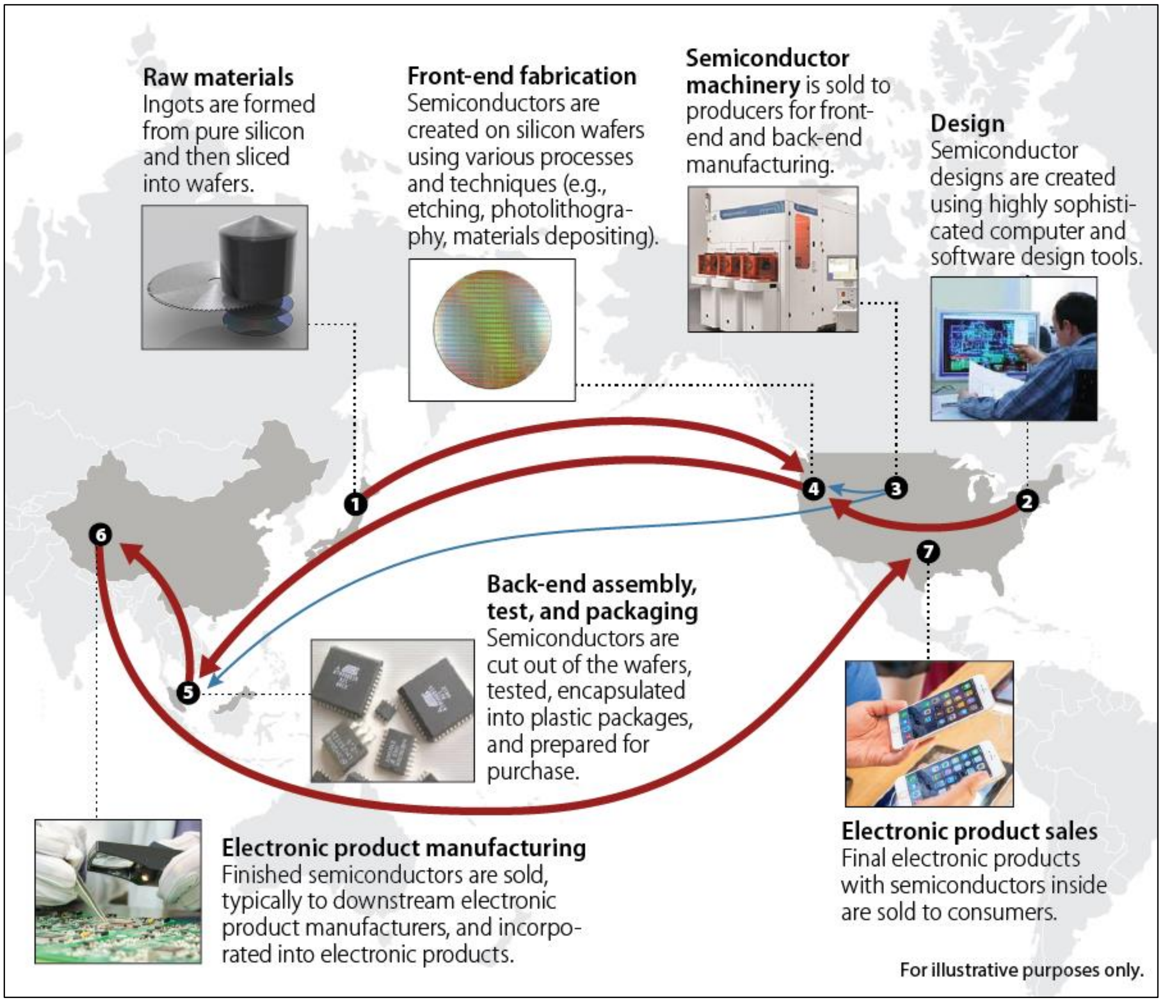
[26] The front-end manufacturing process covers everything from the creation of the silicon wafer to the production of integrated circuits on the wafer, and includes lithography, deposition, etching and striping, inspection and doping.

[27] Falan Yinug, *Challenges to Foreign Investment in High-Tech Semiconductor Production in China*, USITC, May 2009, p. 16, https://www.usitc.gov/publications/332/journals/semiconductor_production.pdf.

[28] The year-end forecast for sales of semiconductor manufacturing equipment in North America was $5.6 billion in 2015. SEMI, "Semiconductor Equipment Sales Forecast," December 15, 2015.

[29] U.S. Government Accountability Office (GAO), *Export Controls: Challenges with Commerce's Validated End-User Program May Limit Its Ability to Ensure that Semiconductor Equipment Exported to China is Used as Intended*, GAO-08-1094, September 2008, p. 1, http://www.gao.gov/assets/290/282096.pdf.

Figure 2. Typical Global Semiconductor Production Pattern



Source: CRS, adapted from information provided by SIA.

Notes: This diagram is for illustrative purposes only. Numbered circles do not necessarily reflect where specific production, services, or sales take place.

The U.S. Semiconductor Manufacturing Industry

Nationally, there were about 820 firms involved in semiconductor and related device manufacturing in 2013.[30] The U.S. semiconductor industry's contribution to the U.S. economy measured by value added was $27.2 billion in 2014, accounting for approximately one percent of U.S. manufacturing value added.[31] Declining chip prices remain a challenge for semiconductor manufacturers as producers can continually manufacture more powerful chips that contain more functionality at lower prices and the price of semiconductors has fallen consistently over time. For example, according to the Bureau of Labor Statistics (BLS) producer price index, a measure

[30] U.S. Census Bureau, *Statistics of U.S. Businesses*, 2013, http://www.census.gov/econ/susb/.

[31] An industry's value added measures its contribution to the economy. Industry value added based on NAICS 334413 from the U.S. Census Bureau's Annual Survey of Manufacturers.

of price changes by industry, semiconductor prices, adjusted for quality and performance, decreased by 46% between 2005 and 2015.[32] Consequently, to maintain or grow their revenue, chip producers must find new markets for their products.

R&D Spending

Because of the constant pressure to innovate, semiconductor manufacturers invest heavily in R&D. According to SIA, industry-wide investment rates in R&D range between 15-20% of sales.[33] In 2012, U.S. semiconductor manufacturers devoted 19.4% of their domestic sales to R&D, which was higher than other large industrial sectors, including pharmaceuticals and medicines and computers and electronic products, based on the most recent available statistics from the National Science Foundation (NSF).[34] By comparison, R&D intensity for all manufacturing industries was 3.6% in 2012. According to an analysis of R&D expenditures by the SIA, R&D performed by semiconductor firms tends to be consistently high, regardless of cycles in annual sales.[35]

In December 2015, a long-standing tax issue for the industry was resolved when Congress made the research and experimentation tax credit (widely referred to as the R&D tax credit) permanent, rather than expiring periodically, as it had over the last few decades.[36] Semiconductor industry lobbyists asserted that making the R&D tax credit permanent will encourage semiconductor companies (and other manufacturers) to plan sustained, long-term R&D efforts.[37]

Employment

According to BLS, the U.S. semiconductor and related device manufacturing industry employed 180,700 workers in 2015, down 38% from 292,100 in 2001.[38] This represented 1.5% of total manufacturing employment in the United States in 2015. The semiconductor manufacturing workforce earned an average wage of $138,100 in 2015, more than twice the average for all U.S. manufacturing workers ($64,305).[39] These employment and wage figures do not include all workers in the industry, as BLS counts employees of fabless semiconductor firms as wholesale trade workers rather than manufacturing workers.[40]

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[32] Semiconductor price data based on NAICS 334413 from the U.S. Bureau of Labor Statistics (BLS) producer price index program, http://www.bls.gov/ppi/.

[33] SIA and Nathan Associates, *Beyond Borders: The Global Semiconductor Value Chain*, May 2017, p. 5.

[34] National Science Foundation (NSF), Domestic R&D Paid by the Company and Performed by the Company and Others as a Percentage of Domestic Net Sales, by Industry and Company Size: 2012, Table 19, *Business Research and Development Innovation: 2012*, October 29, 2015, http://www.nsf.gov/statistics/2016/nsf16301/pdf/tab19.pdf.

[35] SIA, *The U.S. Semiconductor Industry*, 2016 Factbook, April 1, 2016, pp. 18-19.

[36] The permanent tax credit was included in the Consolidated Appropriations Act, 2016 (P.L. 114-113), enacted December 18, 2015. The R&D tax credit has expired 17 times since it was first established in 1981. For more information see, CRS Report RL31181, *Research Tax Credit: Current Law and Policy Issues for the 114th Congress*, by Gary Guenther.

[37] SIA, "Semiconductor Industry Hails Passage of Permanent R&D Credit," press release, December 18, 2015, http://www.semiconductors.org/news/2015/12/18/press_releases_2015/semiconductor_industry_hails_passage_of_permanent_r_d_credit/.

[38] BLS, Quarterly Census of Employment and Wages (QCEW) for NAICS 334413, http://www.bls.gov/cew/.

[39] Average wage data are from BLS's QCEW program. 2015 data are preliminary.

[40] SIA, *U.S. Semiconductor Industry Employment*, April 2013, p. 3, http://www.semiconductors.org/clientuploads/Jobs%20Rollout/Jobs%20Issue%20Paper_April_2013.pdf.

In 2015, nearly one-quarter of all domestic semiconductor manufacturing jobs were in California. Other states accounting for substantial shares of total U.S. semiconductor manufacturing employment include Texas, Oregon, Arizona, Massachusetts, Idaho, and New York.[41]

Semiconductor Manufacturing Locations

Semiconductor manufacturing is highly capital intensive. To produce each new generation of chips, and to benefit from the cost advantage offered by larger wafers, manufacturers must invest in new facilities and equipment and reinvest in existing facilities and equipment. A state-of-the-art plant to make 300-millimeter (12-inch) wafers, the size that allows maximum production efficiency, can cost as much as $10 billion.[42] Between 2011 and 2014, the U.S. Census Bureau reports, the sector's domestic expenditures for new plants and equipment ranged from a low of $17 billion in 2013 to a high of around $22 billion in 2011.[43]

In 2015, about three-fourths of the world's 300mm semiconductor fabrication capacity was located in South Korea, Taiwan, Japan, and China. By comparison, North America (mainly the United States) accounted for about 13% of worldwide 300mm wafer fabrication production capacity in 2015 (see **Table 1**).[44]

Table 1. Global Wafer Fabrication Capacity

300mm Equivalent Wafer Capacity by Country/Region

Country/Region	2015
South Korea	26%
Taiwan	24%
Japan	18%
North America	13%
China	8%
Europe	3%
Rest of World (ROW)	9%

Source: IC Insights, Global Wafer Capacity 2016-2020, http://www.icinsights.com/services/global-wafer-capacity/report-contents/.

In a 2012 report, the National Academy of Sciences noted the share of total worldwide fabrication capacity located in the United States had dropped from 42% in 1980, to 30% in 1990, and to 16%

[41] State employment data are from the BLS QCEW program.

[42] Angelo Zino, *Semiconductors & Semiconductor Equipment: Industry Surveys*, S&P Capital IQ, May 2016, p. 47; Jim Handy, "Why Are Computer Chips So Expensive? Why Are Computer Chips So Expensive?," *Forbes*, April 30, 2014. The industry anticipates a shift to 450mm wafer production, which could reduce costs by 30% and allow for greater throughput. Most industry executives expect this shift after 2020. See, KPMG, Global *Semiconductor Outlook 2016: Seismic Shifts Underway*, p.20, http://www.kpmg.com/US/en/industry/technology/Documents/kpmg-global-semiconductor-outlook-2016.pdf.

[43] Capital expenditures based on NAICS 3344 (semiconductors and other electronic component manufacturing) from the U.S. Census Bureau's Annual Capital Expenditures Survey, http://www.census.gov/programs-surveys/aces.html.

[44] IC Insights, *S. Korean and Taiwanese Companies Control 56% of Global 300mm Fab Capacity*, December 18, 2014, p. 2, http://www.icinsights.com/data/articles/documents/742.pdf.

in 2007. The reasons behind the shift, according to industry experts, were the rapid expansion of Asian semiconductor companies and offshore investment by U.S. companies.[45]

U.S.-headquartered semiconductor fabrication companies conduct more than half of their front-end wafer processing operations in the United States. **Table 2** lists U.S. semiconductor fabs capable of producing 300mm silicon wafers. According to one recent study, semiconductor producers base site selection decisions on tax advantages, supply of engineering and technical talent, quality of water supply, reliability of utilities, environmental permitting process and other regulations, cost of living for employees, and legal protection of intellectual property.[46]

Table 2. 300mm (12-inch) Semiconductor Fabs in the United States, 2015

Company	Number of Facilities	Location	Products
Intel Corporation	2	Chandler, AZ	Logic/Microprocessor Unit (MPU)
Micron Technology	1	Boise, ID	Memory/DRAM/Flash-3D NAND
Intel Corporation	1	Albuquerque, NM	Logic/MPU
GlobalFoundries	2	Malta, NY	Foundry/Dedicated
GlobalFoundries	1	East Fishkill, NY	Foundry/Dedicated
Intel Corporation	4	Hillsboro, OR	Logic/MPU
Samsung	1	Austin, TX	Foundry/System Large Scale Integration (LSI)
Texas Instruments	1	Richardson, TX	Analog/Linear
Texas Instruments	1	Dallas, TX	Analog/Mixed Signal
Micron Technology	1	Lehi, UT	Memory/Flash
Micron Technology	2	Manassas, VA	Memory/DRAM

Source: Semiconductor Equipment and Materials International (SEMI), an industry trade group that represents the manufacturers of semiconductor and flat panel display equipment and materials, provided CRS with a list of semiconductor fabrication plants by email on March 18, 2016 from its Fab Construction database.

Notes: Silicon wafers are available in a variety of sizes. The size of the wafer is an important element in semiconductor manufacturing because the number of chips per wafer increases dramatically as the wafer size increases. State-of-the-art fabs produce silicon wafers that are 300mm in width. Moving from a 200mm wafer to a 300mm wafer increases the number of semiconductor chips by a factor of 2.25 times.

Intel conducts 70% of its wafer fabrication in the United States, at facilities in Arizona, New Mexico, and Oregon.[47] Micron is the only DRAM manufacturer that has factories in the United States, with facilities in Idaho, Utah, and Virginia.[48] Texas Instruments has manufacturing facilities in Maine and Texas.[49] Global Foundries, a company based in California but controlled

[45] Charles Wessner and Alan Wolff, *Rising to the Challenge: U.S. Innovation for the Global Economy*, National Research Council, 2012, p. 340.

[46] Robert C. Leachman and Chien H. Leachman, "Globalization of Semiconductors: Do Real Men Have Fabs, or Virtual Fabs?" in Martin Kenney with Richard Florida, eds., *Locating Global Advantage: Industry Dynamics in the International Economy*. Stanford, CA: Stanford University Press, November 18, 2003, p. 226.

[47] Intel, 2015 Annual 10-K report, p.10.

[48] Micron, 10-K Annual Report, October 27, 2015, p. 20, http://investors.micron.com/. All other domestic producers have either shut down or outsourced their DRAM manufacturing to foundries abroad.

[49] Texas Instruments, *2014 Corporate Citizenship Report*, May 21, 2015, p. 4.

by the Emirate of Abu Dhabi, has acquired U.S. fabs formerly owned by Advanced Micro Devices and IBM Corporation. All of these companies also manufacture overseas.

Most new semiconductor manufacturing capacity is located outside the United States. According to the Semiconductor Equipment and Materials International (SEMI), an industry trade group that represents the manufacturers of semiconductor and flat panel display equipment and materials, of the 36 new fab projects of all sizes planned to be built worldwide between 2015 and 2017, five were planned for the United States, compared to 14 in China. The other projects will be in Southeast Asia (6), Taiwan (6), Japan (2), Europe (2), and South Korea (1).[50]

International Trade

Foreign markets accounted for 83% of semiconductor sales by U.S.-headquartered firms in 2015, reflecting the fact that many end-user industries, such as assembly of computers and consumer electronics, are located mainly in Asia.[51] Total exports of U.S.-made semiconductors and related devices registered $41.8 billion in 2015, a reduction of 2% from the previous year. Appreciation in the value of the U.S. dollar has made American factories' goods more expensive in international markets, potentially contributing to the loss in market share.[52]

Mexico, China, Malaysia, South Korea, and Taiwan ranked as the top five U.S. export markets in 2015. These countries are large producers of consumer electronics, telecommunications equipment, and information and communications technologies, all of which rely heavily on semiconductors as a principal component. According to data from the United States International Trade Commission (USITC), in 2015, semiconductors represented the top U.S. high-tech export by value and the fourth-largest overall export by value, behind civilian aircraft, petroleum refinery products, and automobiles.[53]

Imports of semiconductors totaled $41.7 billion in 2015, expanding 3.3% from a year earlier. Malaysia, China, Taiwan, Japan, and South Korea ranked as the top five import sources for the United States. Of the top five countries from which the United States imports semiconductors, Malaysia contributed the most, accounting for more 30% of all imported semiconductors in 2015. Malaysia is an important offshore location for semiconductor packaging, assembly, and testing, including for U.S.-headquartered semiconductor firms such as Intel.[54] In 2015, 13% of U.S. semiconductor imports were from China, up from 9% in 2009.

Roughly one-third of U.S. semiconductor imports are reexported. This reflects the fact that many electronic products have complex international supply chains; thus, semiconductor products may cross several borders before being incorporated into a final product.

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[50] SEMI provided data to CRS from its proprietary Fab Construction Monitor database. The new fab construction totals include two small LED fabs in the United States.

[51] Falan Yinung, *Made in America: The Facts about Semiconductor Manufacturing*, SIA, August 2015, p. 4. http://blog.semiconductors.org/blog/sia-white-paper-facts-about-semiconductor-manufacturing; SIA, *The Semiconductor Industry Association's Comments to the President's Economic Recovery Advisory Board's Tax Reform Subcommittee*, October 15, 2009, p. 2, https://www.whitehouse.gov/assets/formsubmissions/109/df34744d43114007a53ecfb8479b7898.pdf.

[52] Darryle Ulama, *Earth Potential: International Competition May Outpace Growth Despite Increased Demand*, IBISWorld, Report 33441A: Semiconductor & Circuit Manufacturing in the U.S., December 2015, p. 10.

[53] CRS analysis of U.S. trade data by six-digit NAICS code from the USITC's dataweb.

[54] Luis Abad, Ngozika Amalu, and Ramona Lohan, et al., *The Malaysian Semiconductor Cluster*, Microeconomics of Competitiveness, May 8, 2015, p. 8, http://www.isc.hbs.edu/resources/courses/moc-course-at-harvard/Documents/pdf/student-projects/Malaysia_Semiconductor_Cluster_2015.pdf.

The semiconductor industry supports passage of the Trans-Pacific Partnership (TPP) agreement and successful conclusion of the ongoing Transatlantic Trade and Investment Partnership (TTIP) negotiations with Europe.[55] After years of negotiations, a recent success for the semiconductor industry was the expansion of the World Trade Organization (WTO) Information Technology Agreement (ITA), a plurilateral tariff-cutting agreement focused on trade in information technology goods.[56] Beginning on July 1, 2016, the expanded ITA will eliminate some tariffs immediately and phase out others by January 2024 on 201 information technology products not included in the original 1996 ITA.[57] The newly added products apply to next generation multicomponent semiconductors (MCOs), which currently face global tariff rates which generally range from 2.5% to 8.0% and can be as high as 25.0% in some countries.[58] MCOs are incorporated into a range of electronics such as smart phones, tablets, gaming consoles, e-readers, tire pressure monitors, and hand-held projectors. ITA participants committed to reconvene in 2018 to consider updating the agreement to include additional products and to possibly address non-tariff barriers in the information technology sector.[59] For additional information, see CRS Insight IN10331, *Expansion of WTO Information Technology Agreement Targets December Conclusion*, by Rachel F. Fefer.

Intellectual Property Rights

Major semiconductor producers regularly rank among the top U.S. corporate patent recipients measured by number of patents granted. In 2015, this list included Qualcomm (2,900), Intel (2,046), and Broadcom (1,086), according to data from the U.S. Patent and Trademark Office on patents granted by company.[60] The semiconductor industry supported the Defend Trade Secrets Act (DTSA) of 2015 (P.L. 114-153) enacted on May 13, 2016. The law creates a federal private right to action for trade secret misappropriations (e.g., when an individual acquires a trade secret through improper means, including theft, bribery or espionage).[61] For more information about the protection of trade secrets, see CRS Report R43714, *Protection of Trade Secrets: Overview of Current Law and Legislation*, by Brian T. Yeh.

[55] SIA, *2016 Policy Priorities*, http://www.semiconductors.org/clientuploads/Resources/SIA%202016%20Policy%20Priorities%201%20Pager%20FINAL.pdf.

[56] World Trade Organization (WTO), *WTO Members Conclude Landmark $1.3 Trillion Trade Deal*, December 16, 2015, https://www.wto.org/english/news_e/news15_e/ita_16dec15_e.htm. (A plurilateral agreement involves a subset of countries that often negotiate to liberalize trade in a specific sector.)

[57] The original ITA signed in 1996 was intended to cover all semiconductors and integrated circuits under semiconductor harmonized tariff scheduled (HTS) headings 8541 and 8542, meaning these products entered most markets duty-free. However, the 1996 ITA did not include a mechanism to cover new advanced technology products.

[58] Devi Keller, *The Benefits of Including Multi-Component Semiconductors in an Expanded Information Technology Agreement*, SIA, December 8, 2014, http://blog.semiconductors.org/blog/the-benefits-of-including-mcos-in-an-expanded-information-technology-agreement.

[59] WTO, "Chinese Taipei, Thailand Confirm Acceptance of Landmark IT Deal," press release, July 28, 2015, https://www.wto.org/english/news_e/news15_e/ita_28jul15_e.htm.

[60] U.S. Patent and Trademark Office, *All Technologies Report*, January 1, 1991--December 31, 2015, March 2016, http://www.uspto.gov/web/offices/ac/ido/oeip/taf/all_tech.pdf.

[61] SIA, "Semiconductor Industry Commends Passage of Legislation to Protect Trade Secrets," press release, April 27, 2016, http://www.semiconductors.org/news/2016/04/27/press_releases_2015/semiconductor_industry_commends_passage_of_legislation_to_protect_trade_secrets/.

Congress has addressed the importation of counterfeit products, items marked or marketed as the real thing for branded versions of products, in the Foreign Counterfeit Merchandise Prevention Act (H.R. 236). The bill introduced by Representative Ted Poe would allow customs officials to share information about imported "critical" goods with intellectual property rights (IPR) holders whose copyright and trademark rights might be infringed by imports.[62] In this instance, critical goods are defined as those for which counterfeits pose a danger to the health, safety, or welfare of consumers or national security, including semiconductors. Similar legislation has been introduced in previous Congresses. The semiconductor industry asserts Customs and Border Protection (CBP) has not adequately protected its IPR from growing imports of counterfeit goods, and that CBP efforts to collaborate with the private sector to identify and enforce IPR violations have been inadequate.[63]

Global Competition

East Asia

American companies dominated worldwide production of semiconductors until the 1970s.[64] In the 1980s, when Japan captured the majority of the global DRAM market, the U.S. government alleged that Japanese companies achieved this position due to the Japanese government's protection of its domestic market, stifling the sale of U.S. semiconductors in Japan.[65] The U.S. government responded to this development in several ways, including seeking a bilateral agreement to open the Japanese market to U.S. semiconductors and providing federal funding for a research consortium to support U.S. technological competitiveness in the field. These efforts produced the 1986 U.S.-Japan Semiconductor Agreement and the 1987 formation of SEMATECH (short for Semiconductor Manufacturing Technology), a consortium of semiconductor companies.[66] SEMATECH and"The Japanese Challenge" are discussed later in this report.

Since the early 1990s, Japan's share of the global semiconductor market has fallen significantly. Several Japanese fabs have closed, and some producers have gone bankrupt. In 2015, only three Japanese chipmakers—Toshiba, Renesas Electronics, and Sony—were among the top 20 producers worldwide ranked by revenue.

As the market positions of Japanese companies have declined, companies based elsewhere in East Asia have become prominent global suppliers, mostly in the DRAM segment of the market. South Korea's Samsung Electronics and SK Hynix are now the second- and third-largest semiconductor companies in the world. According to data from Statistica, an industry statistics portal, at the end

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[62] SIA, *Winning the Battle Against Counterfeit Semiconductor Products*, August 2013, http://www.semiconductors.org/clientuploads/Anti-Counterfeiting/SIA%20Anti-Counterfeiting%20Whitepaper.pdf.

[63] U.S. Congress, House Committee on the Judiciary, Subcommittee on Crime, Terrorism, and Homeland Security, *Hearing on* H.R. 4223*, the Safe Doses Act";* H.R. 3668*, the Counterfeit Drug Penalty Enhancement Act of 2011; and* H.R. 4216*, the "Foreign Counterfeit Prevention Act*", 112th Cong., 2nd sess, March 28, 2012, Testimony of Mr. Travis D. Johnson.

[64] National Defense University, *Industry Study: Electronics*, Spring 2015, p. 1.

[65] Douglas A. Irwin, *The Political Economy of Trade Protection*, National Bureau of Economic Research, The U.S.-Japan Semiconductor Trade Conflict, January 1996, p. 7. A version of the chapter is available at http://www.nber.org/chapters/c8717.pdf.

[66] The 1986 U.S.-Japan Semiconductor Agreement included three major provisions: (1) Japan agreed to open its markets to U.S. semiconductors; (2) Japan committed to the goal of a 20% foreign share of the Japanese market by 1992 (which was not reached during the life of the agreement); and, (3) Japan agreed to stop dumping in third markets.

of 2015, Samsung held 46.4% of the global DRAM market, followed by SK Hynix at 27.9%, and Micron at 18.9%.[67] The growth of the South Korean semiconductor industry has been supported and nurtured by government funding and the financial backing of large, family-controlled industrial conglomerates known as chaebols. The chaebols play a central role in South Korea's economy.[68]

Taiwan has become the world's leading location for semiconductor foundry manufacturing. Taiwan's semiconductor foundry industry is dominated by two contract manufacturers, Taiwan Semiconductor Manufacturing Company (TSMC) and United Microelectronics Company (UMC).[69] Both TSMC and UMC were established and directly funded by the Taiwanese government in the 1980s through a variety of grants, low-interest loans, and other subsidies, although both are organized as private enterprises.[70]

China

In 2014, China accounted for close to 57% of the worldwide consumption of integrated circuits.[71] However, the country plays a limited role in the production of semiconductors. A 2014 study by the East-West Center, a nonpartisan research group established by Congress, reported that up to 80% of the semiconductors used in Chinese electronics manufacturing are imported.[72]

According to a PricewaterhouseCoopers (PWC) report on China's semiconductor industry, semiconductor manufacturers in China, including indigenous Chinese firms and multinational semiconductor firms, accounted for 13.4% of the worldwide semiconductor industry by revenue in 2014, up from 12.0% in 2013 and 11.6% in 2012.[73] In 2014, China's semiconductor industry revenues rose to $77.3 billion, up from $40.5 billion in 2013 and $34.2 billion in 2012.

Currently, non-Chinese semiconductor companies dominate the Chinese market. Dieter Ernst of the East-West Center notes, "China's domestic semiconductor manufacturing (i.e., wafer fabrication) technology and capabilities have failed to keep up with the country's IC design capabilities and needs."[74] The same report notes China's wafer fabrication plants "are using older technology and used equipment, reflecting China's focus on light-emitting diode (LED) and other

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[67] Statistica, The Statistics Portal, "Global Market Share of the DRAM Chip Market from 1st Quarter 2011 to 1st Quarter 2016 by Vendor," http://www.statista.com/statistics/271726/global-market-share-held-by-dram-chip-vendors-since-2010/.

[68] Nayanee Gupta, David W. Healey, and Aliza M. Stein, et al., *Innovation Policies of South Korea*, Institute for Defense Analyses, August 2013, https://www.ida.org/~/media/Corporate/Files/Publications/STPIPubs/ida-d-4984.ashx.

[69] Taiwan Semiconductor Industry Association, *Overview of Taiwan Semiconductor Industry*, 2015, p. 9, http://www.tsia.org.tw/Uploads/2015%20Overview-Final.pdf.

[70] Tain-Jy Chen, *Taiwan's Industrial Policy Since 1990*, Department of Economics, National Taiwan University, April 2014, p. 9.

[71] PWC, *China's Impact on the Semiconductor Industry: 2015 Update*, October 2015, p. 5, https://www.pwc.com/gx/en/technology/pdf/china-semicon-2015-report1-3.pdf.

[72] Dieter Ernst, *From Catching Up to Forging Ahead? China's Prospects in Semiconductors*, East-West Center, November 2014, p. 7, http://www.eastwestcenter.org/system/tdf/private/ernst-semiconductors2015_0.pdf?file=1&type=node&id=35320.

[73] PricewaterhouseCoopers (PWC), *A Decade of Unprecedented Growth: China's Impact on the Semiconductor Industry 2014 Update*, January 2015, p. 18, http://www.pwc.com/gx/en/technology/chinas-impact-on-semiconductor-industry/assets/china-semicon-2014.pdf.

[74] Dieter Ernst, *From Catching Up to Forging Ahead: China's Policies for Semiconductors*, East-West Center, 2015, p. 7, http://www.eastwestcenter.org/system/tdf/private/ernst-semiconductors2015_0.pdf?file=1&type=node&id=35320

applications that do not require leading-edge semiconductors."[75] Similarly, an analysis of the Chinese integrated circuit market by IBISWorld, a market research firm, found that many Chinese chips are "low-end."[76]

As shown in **Table 3**, of the 94 advanced 300mm wafer fabrication plants in operation worldwide in 2015, only nine were located in China.[77] Of these, three were owned by foreign companies: Intel, Samsung, and SK Hynix. In addition, Taiwanese semiconductor manufacturer TSMC has announced its intention to build a 300mm fab facility in China.[78]

Table 3. Worldwide 300mm Semiconductor Fab Count

Number of Operating Fabs by Country or Region

Country/Region	2011	2013	2015
Taiwan	21	23	28
United States	15	16	17
Japan	16	16	17
South Korea	10	10	12
China	7	7	9
Europe & Mideast	7	6	6
Southeast Asia	4	4	5
Total	80	82	94

Source: SEMI Worldwide Fab Forecast, April 2016. SEMI provided these statistics to CRS by email on April 26, 2016.

In June 2014, the Chinese central authorities published an ambitious plan, *Guidelines to Promote National Integrated Circuit Industry Development*, "with the goal of establishing a world-leading semiconductor industry in all areas of the integrated circuit supply chain by 2030."[79] The document includes measures to support an aggressive growth strategy, with the goal of meeting 70% of China's semiconductor demand from domestic production by 2025.[80]

To make China less dependent on imported chips, according to McKinsey & Company, the Chinese government intends to spend about $100 billion to $150 billion on the development of its semiconductor industry.[81] Among its objectives is to turn local chip manufacturers such as Semiconductor Manufacturing International Corporation (SMIC), which now operates three

[75] Ibid, p. 10.

[76] IBISWorld, *Integrated Circuit Manufacturing in China*, April 2016, p. 6.

[77] PWC, *China's Impact on the Semiconductor Industry: 2015 Update*, Technology Institute Full Report, March 2016, p. 24, http://www.pwc.com/gx/en/technology/pdf/china-semicon-2015-report-1-5.pdf.

[78] Alan Patterson, "TSMC Aims to Build Its First 12-inch Fab in China," *EE Times*, December 17, 2015.

[79] International Trade Administration (ITA), *2015 Top Markets Report: Semiconductors and Semiconductor Manufacturing Equipment,* A Market Assessment Tool for U.S. Exporters, July 2015, p. 13.

[80] "Chips on their Shoulders," *The Economist*, January 23, 2016.

[81] Christopher Thomas, *A New World Under Construction: China and Semiconductors*, McKinsey & Company/, November 2015 http://www.mckinsey.com/global-themes/asia-pacific/a-new-world-under-construction-china-and-semiconductors.

300mm fabs in China, Shanghai Huali Microelectronics Corporation (HMLC), and Wuhan Xinxin Semiconductor Manufacturing (XMC) into major global competitors.[82]

In the past, massive efforts by the Chinese government to spur national champions have failed to bring about the desired results. China faces significant barriers to advanced production in semiconductors. Export controls and other policy barriers in Taiwan, South Korea, and the United States inhibit or prohibit the transfer of the latest technologies to Chinese firms. In 2015, for example, the United States blocked the sale of a number of advanced microprocessors to China over concerns about their use in Chinese supercomputers.[83] The extreme complexity of advanced semiconductors requires a high degree of manufacturing skill, and relatively small producers may lack the economies of scale that are important to driving down unit costs.

Consistent with China's integrated circuit development plan, several Chinese companies have pursued acquisitions of foreign companies. In 2015, Tsinghua Unigroup, a Chinese state-owned enterprise (SOE), proposed to acquire Micron Technologies for $23 billion.[84] After several media outlets reported on the proposed acquisition, some Members of Congress raised concerns with Secretary of the Treasury Jacob Lew about the potential national security and economic ramifications of allowing a Chinese SOE to acquire a major U.S. technology firm, especially the principal American manufacturer of computer memory chips."[85] The acquisition was never realized. In addition, Tsinghua has sought to acquire three Taiwan-based chip packaging companies and reportedly targeted SK Hynix.[86] In 2016, state-backed Chinese investors abandoned a bid to buy one of America's oldest semiconductor manufacturers, Fairchild Semiconductor, and a unit of Tsinghua terminated a plan to buy 15% of Western Digital, which makes hard disk drives.[87]

It is not known whether any of the proposed transactions involving Chinese buyers faced objections from the Committee on Foreign Investment in the United States (CFIUS). The inter-agency committee reviews transactions that could result in control of a U.S. business by a foreign person to determine their potential effect on national security.

Europe

Europe's semiconductor industry includes firms such as STMicroeletronics (formed in 1986 by the merger of SGS Microelectronica of Italy and Thomson Semiconductor of France), Infineon Technologies (formed in 1999 as a spinoff from Siemens' semiconductor operations), and NXP Semiconductors (founded by Philips in 2006). These three European-headquartered firms ranked

[82] SMIC, *SMIC Presentation*, March 2016, p. 10, http://www.smics.com/download/ir_presentation.pdf.

[83] Department of Commerce, Bureau of Industry and Security, "Addition of Certain Persons to the Entity List; and Removal of Person from the Entity List Based on a Removal Request," 80 *Federal Register* 8524-8529, February 18, 2015.

[84] Allison Gatlin, "Micron Snubs Tsinghua, Favors Another Chinese Partnership: Analyst," *Investor's Business Daily* , February 16, 2016, http://www.investors.com/news/technology/micron-snubs-tsinghua-favoring-another-chinese-partnership-analyst/.

[85] "CFIUS Likely to Investigate, Require Changes if Chinese SOE Vies for Micron," *Inside U.S. Trade*, August 28, 2015.

[86] "SK-Hynix Says Reject Tsinghua Unigroup Collaboration Offer," *Reuters*, November 26, 2015.

[87] James Fontanella-Khan, "Fairchild rejects $2.6bn Chinese offer," *Financial Times*, February 16, 2016. Joshua Jamerson and Eva Dou, "Chinese Firm Ends Investment in Western Digital, Complicating SanDisk Tie-Up," *Wall Street Journal*, February 23, 2016.

among the world's top 20 semiconductor firms by revenue in 2015.[88] Measured by advanced 300mm wafer fabrication production capacity, Europe accounted for 3.0% of worldwide production in 2015 (see **Table 1**).[89] European-headquartered semiconductor companies tend to specialize in niche markets such as semiconductors for automobiles and industrial electronics.[90] According to a 2013 communication by the European Commission, Europe made up about 50% of worldwide automotive electronics production and around 35% of global industrial electronics production.[91] The Commission also stated that Europe is strong in manufacturing electronics for energy applications, accounting for about 40% of global production in that market, and in designing electronics for mobile telecommunications. Of the $335 billion in global semiconductor sales, European-headquartered semiconductor firms accounted for about $34 billion in sales in 2015, according to figures from WSTS.[92]

In May 2013, the Commission announced an initiative to support the European semiconductor industry.[93] The initiative, set to run from 2014 to 2020, aims to increase Europe's share of global semiconductor manufacturing to at least 20% by the end of the decade by providing $11 billion (€10 billion) in public and private funding for R&D activities that it hopes will trigger about $113 billion (€100 billion) in industry investment in manufacturing. The initiative calls for a multipronged approach that includes easier access to capital financing by qualified companies; pooling EU, national, and regional subsidies to enable larger-scale projects; and, improving worker training.[94]

The Federal Role in Semiconductors

The federal government has played a major role in supporting the U.S. semiconductor industry since the late 1940s. That role, however, has changed considerably over time. In the early years, federal support for the nascent industry included research funding; support for the development of increasingly powerful computers; and, serving as an early adopter of semiconductor-enabled technologies, creating a market through defense and space-related acquisitions. From the late 1980s through the mid-1990s, the federal role centered on reversing a perceived loss of U.S. competitiveness in semiconductors through the initiation and funding of an industry research consortium. More recently, the federal role has focused on support for research to extend the life of current semiconductor technologies and to develop the scientific and technological underpinnings for revolutionary successor technologies.

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[88] IHS Global Insight, "Preliminary 2015 Semiconductor Market Shares," press release, December 8, 2015, https://technology.ihs.com/553230/preliminary-2015-semiconductor-market-shares.

[89] IC Insights, Global Wafer Capacity 2016-2020, IC Insights, http://www.icinsights.com/services/global-wafer-capacity/report-contents/.

[90] Page Tanner, *Germany to Drive Growth in European Semiconductor Market*, Market Realist, December 24, 2015, http://marketrealist.com/2015/12/germany-drive-growth-european-semiconductor-industry/.

[91] European Commission, *A European Strategy for Micro- and Nanoelectronic Components and Systems*, May 23, 2013, p. 6, https://ec.europa.eu/digital-single-market/en/news/communication-european-strategy-micro-and-nanoelectronic-components-and-systems.

[92] WSTS, "Worldwide Forecasts the Semiconductor Market to Have Slight Growth by 2018," press release, June 7, 2016, https://www.wsts.org/PRESS/Recent-News-Release.

[93] European Commission, "Electronics Industry Submits Plan to Make Europe a Global Leader in Micro and Nano-Electronics," press release, February 14, 2014, http://europa.eu/rapid/press-release_IP-14-148_en.htm.

[94] The initiative was named 10/100/20 from its three main goals. SEMI, *Supporting Competitive Semiconductor Advanced Manufacturing*, February 24, 2014, http://www.semi.org/eu/sites/semi.org/files/docs/SEMI%20Europe%20News-Feb%2024%202014.pdf.

Early Efforts in Computing

Two developments in the late 1940s, computers and transistors, laid the foundation for development of the semiconductor and computing industries. The first was the Electronic Numerical Integrator and Computer (ENIAC), the first general-purpose electronic digital computer, which was announced in 1946. The Army Ballistic Research Laboratory funded development of the ENIAC at the University of Pennsylvania to calculate artillery firing tables. With semiconductor devices still in the future, the ENIAC used thousands of vacuum tubes, crystal diodes, relays, resistors, and capacitors, making it large enough to fill a 30-by-50-foot room. The second major development came in 1947 when Bell Telephone Laboratories (known broadly as Bell Labs), building on federal World War II research investments, invented the transistor, a semiconductor device capable of regulating the flow of electricity.[95]

For the next decade, engineers sought to increase computer performance by overcoming the "tyranny of numbers," a term referring to the need to connect all of a computer's components to each other, a task requiring the hand-soldering of each connection. As the number of components grew to increase computing power, so did the number of connections required, adding to complexity, cost, and reliability issues. The Army Signal Corps attempted to address these challenges by funding a program which sought to make all components the same size and shape, with the wiring built in, so they could be snapped together to form a circuit without the need for soldering. A different solution was developed in 1958 by Texas Instruments with the invention of the integrated circuit (IC), which incorporated resistors, capacitors, and transistors on a single sliver of the semiconducting element germanium. Shortly thereafter, Fairchild Semiconductor developed a silicon-based IC that included a final layer of metal, parts of which could be removed to create the necessary connections, making it more suitable for mass production.[96] While the invention of the IC was accomplished without direct federal funding, government purchases of ICs for military, space, and other uses supplied the initial demand that allowed manufacturers to reduce costs. As late as 1962, government purchases accounted for 100% of total U.S. IC sales.[97]

The Japanese Challenge

Throughout the 1960s and 1970s, the U.S. semiconductor industry grew rapidly and was largely unchallenged on the world stage. While the U.S. share of global semiconductor *consumption* fell from an estimated 81% in 1960 to around 57% in 1972, the U.S. share of global *production* remained at around 60%.[98] However, the rapid ascent of Japan's semiconductor industry in the early 1980s stirred concerns about the potential decline in the competitive position of the U.S.

[95] Executive Office of the President, National Science and Technology Council, *Technology in the National Interest*, 1996.

[96] Nobelprize.org: The Official Site of the Nobel Prize, "The History of the Integrated Circuit," http://www.nobelprize.org/educational/physics/integrated_circuit/history.

[97] Mowery, *Federal policy and the development of semiconductors, computer hardware, and computer software,* Table 1.

[98] Consumption as measured in value. William F. Finan, *The International Transfer of Semiconductor Technology Through U.S.-Based Firms*, National Bureau of Economic Research, Working Paper No. 118, New York, NY, December 1975, http://www.nber.org/papers/w0118.pdf.

Peter R. Morris, *A History of the World Semiconductor Industry*, The Institution of Engineering and Technology (1989), p. 141.

semiconductor industry. By the late 1980s, the U.S. share of global semiconductor sales fell below 40%.[99]

In 1987, the Defense Science Board's Task Force on Semiconductor Dependency found that U.S. leadership in semiconductor manufacturing was rapidly eroding and that not only was "the manufacturing capacity of the U.S. semiconductor industry…being lost to foreign competitors, principally Japan… but of even greater long-term concern, that technological leadership is also being lost." In addition to the decline in the semiconductor device industry, the task force found that "related upstream industries, such as those that supply silicon materials or processing equipment, are losing the commercial and technical leadership they have historically held in important aspects of process technology and manufacturing, as well as product design and innovation."[100]

The task force recommended the formation of an industry-government consortium to "develop, demonstrate and advance the technology base for efficient, high yield manufacture of advanced semiconductor devices." Describing this as the "principal and most crucial recommendation of the Task Force," the report estimated that "the initial capitalization of the Institute by its industrial members would be on the order of $250 million," and recommended federal support of approximately $200 million per year for five years through the Department of Defense.[101]

In 1987, 14 U.S. semiconductor firms founded the SEMATECH (short for Semiconductor Manufacturing Technology) research consortium in Austin, TX. From FY1988 to FY1996, Congress provided a total of approximately $870 million to SEMATECH through the Defense Advanced Research Projects Agency (DARPA), generally matched by contributions from the industry participants.[102]

By 1994 the U.S. semiconductor industry share of the global market had begun to grow again. According to the National Academy of Sciences, "SEMATECH was widely perceived by industry to have had a significant impact on U.S. semiconductor manufacturing performance in the 1990s."[103] A 1992 evaluation by the Government Accounting Office of the federal partnership in SEMATECH's found that:

> SEMATECH has shown that a government-industry R&D consortium can help improve a U.S. industry's technological position by developing advanced manufacturing technology. Whether this can be replicated and what conditions would lead to this result in other cases is uncertain.[104]

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[99] National Research Council, Committee on Comparative National Innovation Policies: Best Practice for the 21st Century, *Rising to the Challenge: U.S. Innovation Policy for the Global Economy*, 2012, http://www.ncbi.nlm.nih.gov/books/NBK100307.

[100] Department of Defense, Defense Science Board, Task Force on Semiconductor Dependency, *Report of Defense Science Board Task Force on Semiconductor Dependency*, February 1987, http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA178284.

[101] Ibid.

[102] Congressional Research Service, *SEMATECH: Issues and Options* (IB93024), June 12, 1996, by Glenn J. McLoughlin. Report available from the author upon request.

[103] National Research Council, Policy and Global Affairs, Board on Science, Technology, and Economic Policy, Committee on Comparative Innovation Policy: Best Practice for the 21st Century, *21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change: Report of a Symposium*, 2009, p. 8, http://www.nap.edu/download/12194.

[104] U.S. Government Accountability Office, *Federal Research: Lessons Learned from SEMATECH*, "Highlights," RCED-92-283, September 28, 1992, http://www.gao.gov/products/RCED-92-283.

Among SEMATECH's leading detractors was Cypress Semiconductor chief executive officer T.J. Rodgers. In a 1998 paper, Rodgers asserted that SEMATECH's federal funding was a subsidy to large, wealthy companies; that hundreds of smaller semiconductor firms were excluded from participating in SEMATECH due to its minimum $1 million annual dues; and that SEMATECH engaged in "hold back" contracts that denied non-SEMATECH firms access to technology that emerged from SEMATECH research. Summing up, Rodgers stated that SEMATECH "used the combined resources of its members and the government to create a competitive advantage, and it kept its secrets from its competitors."[105]

In July 1994, the SEMATECH Board of Directors voted to not accept any additional federal funding after FY1996. The consortium continued to operate on industry funding, allowing foreign-based companies to join. Following the departure of members Intel and Samsung in 2015, SEMATECH was absorbed by the State University of New York Polytechnic Institute and is now based in Albany, NY.

Current Federal Efforts

The federal government has continued to support a wide array of semiconductor research activities.

A major area of research has focused on a successor to complementary metal–oxide–semiconductor (CMOS) technology, which has been the basis of semiconductor manufacturing for half a century. Research and development leading to a continual reduction in the size of components on each chip has enabled CMOS-based semiconductors to become more powerful, more energy-efficient, and less expensive. However, it is widely believed that "as the dimensions of critical elements of devices approach atomic size, quantum tunneling and other quantum effects [will] degrade and ultimately prohibit further miniaturization of conventional devices."[106] This has spurred additional federal efforts to develop other semiconductor technologies.

In July 2015, President Obama issued an executive order establishing the National Strategic Computing Initiative (NSCI) "to create a cohesive, multi-agency strategic vision and federal investment strategy, executed in collaboration with industry and academia, to maximize the benefits of HPC [high performance computing] for the United States." A key objective of the NSCI is to establish, "over the next 15 years, a viable path forward for future HPC systems even after the limits of current semiconductor technology are reached."[107] The executive order designates the U.S. Department of Energy (DOE), the National Science Foundation (NSF), and the Department of Defense (DOD) as the lead agencies, and designates the Intelligence Advanced Research Projects Activity and National Institute of Standards and Technology (NIST) as foundational research and development agencies.

Other federal efforts include:

- **Semiconductor Technology Advanced Research Network (STARnet).** STARnet, a partnership between DARPA and semiconductor and defense

[105] Cato Institute, "T.J. Rodgers, *Silicon Valley Versus Corporate Welfare*, Cato Institute Brief Papers, Briefing Paper No. 37 , April 27, 1998, http://www.cato.org/pubs/briefs/bp-37.html.

[106] National Science and Technology Council (NSTC), Subcommittee on Nanoscale Science, Engineering, and Technology (NSET), *The National Nanotechnology Initiative: Supplement to the President's FY2017 Budget*, p. 17, http://www.nano.gov/sites/default/files/pub_resource/nni_fy17_budget_supplement.pdf.

[107] Executive Order 13702, "Creating a National Strategic Computing Initiative," 80 *Federal Register* 46177-46180, July 29, 2015.

companies, is a collaborative network of research centers focused on "finding paths around the fundamental physical limits threatening the long-term growth of the microelectronics industry."[108]

- **Secure and Trustworthy Cyberspace: Secure, Trustworthy, Assured and Resilient Semiconductors and Systems (SaTC: STARSS)**. SaTC: STARSS is a joint research effort of NSF and the Semiconductor Research Corporation (SRC) [109] focused on new strategies for semiconductor architecture, specification and verification, to increase resistance and resilience to tampering and to improve authentication throughout the supply chain.[110]
- **Nanoelectronics for 2020 and Beyond.** Nanoelectronics for 2020 and Beyond is an effort organized under the National Nanotechnology Initiative (NNI)[111] "to discover and use novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures."[112] Congress has provided approximately $530 million for the Nanoelectronics for 2020 and Beyond initiative since FY2011, primarily through NSF, DOD, and NIST. Specific projects include the Nanoelectronics Research Initiative, a public-private partnership with the SRC and STARnet.
- **Energy-Efficient Computing: from Devices to Architectures (E2CDA).** E2CDA is a joint initiative between NSF and SRC focused on the development of technologies to reduce the amount of energy it takes to manipulate, store, and transport data.

National Security Concerns

For decades, many have argued that maintaining a domestic manufacturing capability for the most advanced semiconductor products is necessary for national security. Proponents of this view claim dependence by the U.S. military on foreign suppliers of semiconductors, especially those that are hostile or may become hostile to U.S. interests, is not acceptable due to the military's reliance on semiconductors as a vital and ubiquitous component in U.S. weapons and defense systems. However, the high costs of maintaining a domestic semiconductor production capability for critical military inputs may result in more expensive weapons systems.[113]

In 2003, then-Deputy Secretary of Defense Paul Wolfowitz wrote in an unclassified memo the "country needs a defense industrial base that includes leading edge, trusted commercial suppliers for critical integrated circuits used in sensitive defense weapons, intelligence, and

[108] Semiconductor Research Corporation, website, "STARnet Research," https://www.src.org/program/starnet.

[109] SRC is a U.S. non-profit research consortium established by semiconductor companies in 1982 to "define relevant research directions, explore potentially important new technologies (and transfer results to industry), [and] generate a pool experienced faculty and relevantly educated students." (Source: Semiconductor Research Corporation, *SRC: Celebrating 30 Years*, https://www.src.org/src/story/src-celebrating-30-years-expanded.pdf.

[110] NSF, Secure and Trustworthy Cyberspace: Secure, Trustworthy, Assured and Resilient Semiconductors and Systems Program Solicitation (NSF 14-528), http://www.nsf.gov/pubs/2014/nsf14528/nsf14528.htm#pgm_desc_txt.

[111] An NNI signature initiative is a mechanism for combining the expertise, capabilities, and resources of federal agencies to accelerate research, development, or insertion, and overcome challenges to the application of nanotechnology-enabled products.

[112] NSTC, NSET, *The National Nanotechnology Initiative: Supplement to the President's FY2017 Budget*, p. 17, http://www.nano.gov/sites/default/files/pub_resource/nni_fy17_budget_supplement.pdf.

[113] Daniel M. Marrujo, *Trusted Foundry Program*, Defense Microelectronics Activity, October 31, 2012, pp. 11-12.

communications systems."[114] As a follow-up to the memo, the Department of Defense (DOD) implemented a trusted supplier program (originally named the trusted foundry program) in 2004, whereby the government pays a fee to U.S. companies to guarantee the access and reliability of components that are important to national defense.[115]

Under the program, IBM's fabrication facilities supplied advanced semiconductors to DOD as the sole source contractor. In 2014, however, IBM announced that the United Arab Emirates-owned GlobalFoundries would acquire its unprofitable microelectronics fabrication facilities in Vermont and New York.[116] The Committee on Foreign Investment in the United States (CFIUS)[117] reviewed the transaction and in July 2015 said that it would not prohibit the acquisition.[118] GlobalFoundries also obtained the appropriate accreditations to be a DOD trusted supplier. According to recent news reports, in June 2016, DOD reached a seven-year agreement with GlobalFoundries to supply microchips until 2023.[119]

In October 2015, the House Armed Services Subcommittee on Oversight and Investigations held a hearing that considered the long-term viability of the DOD trusted supplier program in light of the shrinking number of domestic microelectronics manufacturers and other ways the semiconductor industry has changed.[120] Future policy options under consideration include identifying additional U.S.-based trusted foundries with leading-edge manufacturing capability; exploring alternative manufacturing approaches, which may incorporate non-U.S. made semiconductor parts; or, establishing a government-owned fabrication facility.[121] Beyond manufacturing, the trusted supplier program also includes firms that provide other services in the semiconductor supply chain, including design, assembly, and testing.[122]

Despite national security concerns, DOD is heavily reliant on the commercial supply chain, which includes many non-U.S. suppliers, for most of its electronic hardware and the trusted

[114] Department of Defense, *Defense Science Board Task Force on High Performance Microchip Supply*, December 2005, pp. 87-88.

[115] The trusted supplier program is jointly managed by DOD and the National Security Agency. DOD's Defense Microelectronics Activity (DMEA) certifies and accredits firms as trusted suppliers in the areas of state-of-the-art microelectronics design and manufacturing and other capabilities when they are custom-designed, custom-manufactured, or tailored for a specific DOD military end use. For a list of the more than 70 DMEA- trusted suppliers, see http://www.dmea.osd.mil/trustedic.html.

[116] GlobalFoundries is owned by the government of Abu Dhabi in the United Arab Emirates. IBM, "GlobalFoundries to Acquire IBM's Microelectronics Business," press release, October 20, 2014, https://www-03.ibm.com/press/us/en/pressrelease/45110.wss.

[117] CFIUS is authorized to conduct national security reviews of foreign acquisitions of U.S.-based firms under section 721 of the Defense Production Act of 1950. The President has the authority to suspend or block foreign mergers and acquisitions involving U.S.-based firms if they present credible threats to national security, which includes the loss of reliable suppliers of defense-related goods and services. The CFIUS process is legally bound by strict confidentiality requirements, and it does not disclose whether a notice has been filed or the results of any filing. However, it does provide a confidential report to Congress upon the conclusion of its review.

[118] GlobalFoundries, "GlobalFoundries Obtains U.S. Government Clearance for IBM Microelectronics Business Acquisition," press release, June 29, 2015, http://www.globalfoundries.com/newsroom/press-releases/2015/06/29/globalfoundries-obtains-u.s.-government-clearance-for-ibm-microelectronics-business-acquisition.

[119] Doug Cameron, "Pentagon Hires Foreign Chips Supplier," *Wall Street Journal*, June 5, 2016.

[120] U.S. Congress, House Committee on Armed Services, Subcommittee on Oversight and Investigations, *Assessing DOD's Assured Access to Micro-Electronics in Support of U.S. National Security Requirements*, 114th Cong., 2nd sess., October 28, 2015.

[121] General Accountability Office, *Trusted Defense Microelectronics: Future Access and Capabilities are Uncertain*, GAO-16-185%, October 2015, pp. 4-5.

[122] The commercial semiconductor packaging and assembly industry is located mainly in Asia.

supplier program is used for only a small fraction of the chips in defense systems. In summer 2015, DOD's Office of Manufacturing and Industrial Base Policy began a study on the microelectronics industrial base, which when finished is expected to include recommendations on strategies to increase DOD's access to trusted microelectronics manufacturers.[123]

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[123] For additional background, see Manufacturing and Industrial Base Policy (MIBP), http://www.acq.osd.mil/mibp/.