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Semiconductors: U.S. Industry, Global Competition, and Federal Policy

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SUMMARY

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Semiconductors: U.S. Industry, Global Competition, and Federal Policy

Semiconductors, tiny electronic devices based primarily on silicon or germanium, enable nearly all industrial activities, including systems that undergird U.S. technological competitiveness and national security. Many policymakers see U.S. strength in semiconductor technology and fabrication as vital to U.S. economic and national security interests. The U.S. semiconductor industry dominates many parts of the semiconductor supply chain, such as chip design. Semiconductors are also a top U.S. export. Semiconductor design and manufacturing is a global enterprise with materials, design, fabrication, assembly, testing, and packaging operating across national borders. Six U.S.-headquartered or foreign-owned semiconductor companies currently operate 20 fabrication facilities, or fabs, in the United States. In 2019, U.S.-based semiconductor manufacturing directly employed 184,600 workers at an average wage of $166,400.

Some U.S.-headquartered semiconductor firms that design and manufacture in the United States also have built fabrication facilities overseas. Similarly, U.S.-headquartered design firms that do not own or operate their own fabrication facilities contract with foreign firms located overseas to manufacture their designs. Much of this overseas capacity is in Taiwan, South Korea, and Japan, and increasingly in China. Some Members of Congress and other policymakers are concerned that only a small share of the world's most advanced semiconductor fabrication production capacity is in the United States. Other have become increasingly concerned about the concentration of production in East Asia and related vulnerability of semiconductor supply chains in the event of a trade dispute or military conflict and other risks such as product tampering and intellectual property theft.

Some Members of Congress and other U.S. policymakers have expressed concerns about the economic and military implications of a loss of U.S. leadership in semiconductors. China's state-led efforts to develop an indigenous vertically integrated semiconductor industry are unprecedented in scope and scale. Many policymakers are concerned that these efforts, if successful, could significantly shift global semiconductor production and related design and research capabilities to China, undermining U.S. and other foreign firms' leading positions. Although China's current share of the global industry is still relatively small and its companies produce mostly low-end chips, China's industrial policies aim to establish global dominance in semiconductor design and production by 2030. Moreover, Chinese semiconductor competencies could support a range of technology advancements, including military applications. Another issue for policymakers is how to address competing interests: China is an important market for U.S. semiconductor firms but U.S. and foreign industry are helping to advance China's capabilities. China's government outlays (an estimated $150 billion to date) and its role as a central production point for global consumer electronics are generating strong incentives and pressures on U.S. and foreign firms to focus on China. The Chinese government views access to foreign capabilities in the near term as a key pathway to accelerate China's indigenous development. Also of concern to many are China's state-led efforts to acquire companies and access semiconductor technology through both licit and illicit means; targeted intellectual property (IP) theft; and technology-transfer pressures.

Issues before Congress include the appropriate role of government in assisting U.S. industry; how best to focus federal financial assistance; the amount of funding each proposed activity would need to accomplish its goals for sustaining U.S. semiconductor competitiveness; how to coordinate and integrate federal activities internally and with initiatives of the U.S. semiconductor and related industries; and how to address China's ambitious industrial plans, trade practices of concern, and the role of U.S. firms in China's emerging semiconductor market. Legislation has been introduced in the 116th Congress to increase federal funding for semiconductor research and development efforts; collaboration between government, industry, and academic partners; and tax credits, grants, and other incentives to spur U.S. production. Two bills under consideration are the Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act (S. 3933/H.R. 7178) and the American Foundries Act (AFA) of 2020 (S. 4130). Some of the provisions of these acts have been included in other bills.

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Introduction

Semiconductors, tiny electronic devices based primarily on silicon or germanium, are a uniquely important enabling technology. They are fundamental to nearly all modern industrial and national security activities, and they are essential building blocks of other emerging technologies, such as artificial intelligence, autonomous systems, 5G communications, and quantum computing. For more than six decades, consistent growth in semiconductor capabilities and performance and concurrent cost reductions have boosted U.S. economic output and productivity and enabled new products, services, and industries.

Since the immediate post-World War II era, the United States has been a global leader in the research, development, design, and manufacture of semiconductors. The United States remains a leader in semiconductor research and development (R&D), chip design, and some aspects of semiconductor manufacturing, but a complex mix of both U.S. and foreign companies makes up the semiconductor supply chain, including fabrication facilities, or fabs. Nevertheless, in 2019, the United States accounted for 11% of global semiconductor fabrication capacity, down from 13% in 2015, continuing a long-term decline from around 40% in 1990.[1]

Many policymakers see the competitiveness of the U.S. semiconductor industry, including domestic production of semiconductors and the retention of manufacturing knowledge, human expertise, and hands-on experience, as vital to U.S. economic and national security interests.[2]

Several factors contribute to congressional concerns about the competitiveness of the U.S. semiconductor industry:

- **Sustaining the ability of the industry to continually improve semiconductor performance while decreasing cost through technological innovation.** Because semiconductors are integral components in almost all industrial activity and fundamental to several emerging technologies, their performance and price affect multiple sectors and the broader U.S. economy.
- **Retaining and growing high-skilled and high-paying semiconductor industry jobs in the United States.** Semiconductor manufacturing jobs in the United States pay twice that of the average U.S. manufacturing job.
- **The movement of many U.S. firms toward a "fabless" business model.** In this model, fabless semiconductor and related firms focus on R&D and design capabilities, while contracting with outside, mostly foreign, fabrication companies.[3] This fabless trend has contributed to a concentration of global chip production among a handful of firms operating fabs in East Asia.
- **U.S. reliance on global supply chains and production concentrated in East Asia and vulnerability to disruption or denial due to trade disputes or**

[1] By 2019, Taiwan, South Korea, and Japan accounted for two-thirds of the world's semiconductor fabrication capacity, and China for 12% of global fabrication.

[2] Executive Office of the President, President's Council of Advisors on Science and Technology, *Report to the President: Ensuring Long-Term U.S. Leadership in Semiconductors*, January 2017, at https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_ensuring_long-term_us_leadership_in_semiconductors.pdf. Also, see Senate floor debate on the National Defense Authorization Act for Fiscal Year 2021, *Congressional Record*, vol. 166, part 128 (July 21, 2020), p. S. 4325.

[3] Beginning in the 1980s, some semiconductor companies began to contract for their fabrication needs rather than maintaining their own fabrication facilities. These firms became known as "fabless" firms. Also, some companies such as Apple that are not classified as semiconductor companies design their own semiconductor chips and contract for their manufacturing.

military conflict. Manufacturing disruptions during the Coronavirus Disease 2019 (COVID-19) pandemic have exacerbated this concern. Successive presidential administrations and many in Congress have asserted the need to retain and expand advanced domestic semiconductor fabrication plants.

- **China's emerging strength in semiconductors supported through a state-led effort to establish itself as a global leader across the supply chain by 2030.** Although China's wafer fabrication is at least a generation behind the global industry in technology, it appears to be catching up through foreign technology acquisition, collaboration, and transfer. This includes the use of joint ventures, licensing agreements, U.S.-led open source technology platforms for chip design, as well as the hiring of foreign talent and the purchase of U.S. equipment and software tools.
- **Assuring access to secure semiconductors for military systems.** Through its Trusted Foundry program, the Department of Defense (DOD) has, for over a decade, relied on a single U.S.-based foundry to supply secure, leading-edge semiconductors. Concerns about the sustainability and adequacy of this approach has generated interest in alternatives, including access to a broader range of commercial, state-of-the-art design and fabrication capabilities.

Although some countries, including the United States, support their domestic semiconductor industry, the scope and scale of China's state-led efforts are unprecedented. China's approach has the potential to shift global semiconductor production and related design and research capabilities to China, a development that could affect the competitiveness of U.S. firms. China's efforts are also of concern to many policymakers because they undermine global rules (e.g., state financing of industry and acquisitions, forced technology transfer, and intellectual property theft). While some aspects of the China semiconductor challenge are unique, the U.S. response to the challenge posed by the Japanese government and its semiconductor industry in the 1980s offers context. For a discussion of the federal policies and investments at that time, including a multiyear, $1.7 billion federal investment in SEMATECH, an industry consortium of U.S. semiconductor firms, see **Appendix A**.

This report discusses the technical challenges the semiconductor industry faces, domestic and global supply chains, secure and trusted production of semiconductors for national security, and federal policies. This report also discusses current legislation to address these concerns, including federal assistance for the domestic semiconductor industry and funding for research and development (R&D) activities.

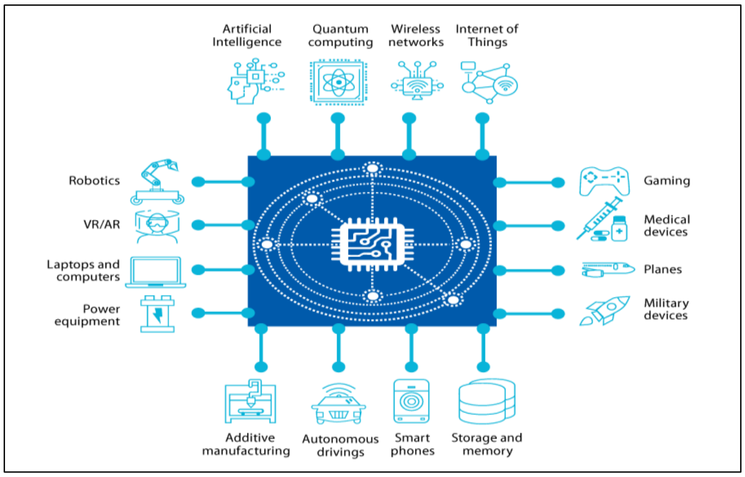
Semiconductor Industry Basics

A semiconductor (also known simply as an integrated circuit, a microelectronic chip, or a computer chip) is a tiny electronic device (generally smaller than a postage stamp) composed of billions of components that store, move, and process data.[4] All of 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 used for many purposes in many types of products—for example, to run software applications and to

[4] Organisation for Economic Co-operation and Development (OECD), *Measuring Distortions in International Markets: The Semiconductor Value Chain*, November 21, 2019, p. 12, at https://www.oecd-ilibrary.org/trade/measuring-distortions-in-international-markets_8fe4491d-en. A semiconductor is a name given to materials with unique electrical properties falling between a conductor and an insulator; products made from these materials are also referred to as semiconductors.

temporarily store documents. Semiconductors provide data storage and communication capabilities of countless other products, including mobile phones, gaming systems, aircraft avionics, industrial machinery, and military equipment and weapons. Many products with roots in mechanical systems—such as manufacturing equipment—heavily depend on chip-based electronics. Modern automobiles illustrate the ubiquitous role of semiconductors in devices that were once only mechanical and chemical in function. According to one analysis, some hybrid electric automobiles may now contain as many as 3,500 semiconductors.[5] Semiconductor chips are fundamental to emerging technological applications such as artificial intelligence, cloud computing, 5G, the Internet-of-Things (IoT), and large-scale data processing and analytics and supercomputing.[6] (See **Figure 1**.)

Figure 1. Semiconductors: An Enabling Technology



Source: Alex Capri, "Semiconductors at the Heart of the U.S.-China Tech War: How a New Era of Techno-Nationalism is Shaking Up Semiconductor Value Chains," Hinrich Foundation, January 2020, p. 13.

[5] David Coffin, Sarah Oliver, and John VerWey, *Building Vehicle Autonomy: Sensors, Semiconductors, Software, and U.S. Competitiveness*, United States International Trade Commission (USITC), Working Paper ID-063, January 2020, p. 8, at https://www.usitc.gov/publications/332/working_papers/autonomous_vehicle_working_paper_01072020-_508_compliant.pdf; and Amanda Lawrence and John VerWey, *The Automotive Semiconductor Market—Key Determinants of U.S. Firm Competitiveness*, USITC, Executive Briefings on Trade, May 2019, at https://www.usitc.gov/publications/332/executive_briefings/ ebot_amanda_lawrence_john_verwey_the_automotive_semiconductor_market_pdf.pdf.

[6] See CRS In Focus IF10608, *Overview of Artificial Intelligence*, by Laurie A. Harris; CRS Report R46119, *Cloud Computing: Background, Status of Adoption by Federal Agencies, and Congressional Action*, by Patricia Moloney Figliola; CRS Report R45485, *Fifth-Generation (5G) Telecommunications Technologies: Issues for Congress*, by Jill C. Gallagher and Michael E. DeVine; CRS In Focus IF11239, *The Internet of Things (IoT): An Overview*, by Patricia Moloney Figliola; and CRS Report RL33586, *The Federal Networking and Information Technology Research and Development Program: Background, Funding, and Activities*, by Patricia Moloney Figliola.

Semiconductor History and Technological Challenges

The federal government played a central role in the development of semiconductors and has engaged in efforts to bolster the competitiveness of the U.S. semiconductor industry and to address unfair trade practices. Early computers (in the 1940s and 1950s) 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 efforts to reduce and simplify the number of these devices. Military applications played a significant role in the research that led to the development of semiconductor technology.

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, 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, in 1965.[7] Moore's Law, which is actually an observation about the pace of development and reduction in chip cost, has held true for decades. It states that the number of transistors that can be cost-effectively included on a dense integrated circuit will double about every 18 months to two years, making semiconductors smaller, faster, and cheaper.[8] This observation has held true for decades. The effects of Moore's Law are evident in short product life-cycles, requiring semiconductor manufacturers to maintain high

Key Semiconductor Dimensions: Feature Size and Wafer Size

This report refers frequently to two key dimensions related to semiconductors. One, **feature size**, relates to the performance of a semiconductor (generally the smaller the feature, the greater the chip performance) and the other, **wafer size**, which relates to the efficiency of semiconductor fabrication (in general, the larger the wafer, the lower the production cost per wafer).

Feature size describes the size of the transistor gate length as measured in billionths of a meter, or nanometers (nm). Feature size is often referred to as the semiconductor technology node, which is used to identify the technology generation of a chip. The extraordinary advances in chip processing power have resulted primarily from continued reductions in the size of the features that can be printed on a chip. Generally, the smaller the feature size, the more powerful the chip, as more transistors can be placed on an area of the same size. This also results in increased processing power per dollar. Many semiconductors manufactured in 2019 were produced at the 14nm and 10nm nodes. Some manufacturers are producing at 7nm and 5nm nodes, with efforts to manufacture at 2nm and 1nm.

Wafer size refers to the diameter of a wafer measured in millimeters (mm). Wafers used in semiconductor fabrication are usually made from thin slices of pure silicon, which serve as the substrate on which semiconductors are manufactured through microfabrication processing steps, such as doping, etching, thin-film deposition, and photolithography. The diameter of a wafer determines its surface area, which in turn determines how many chips can be made on it. A larger wafer diameter allows more amortization of fixed costs, resulting in a lower cost per chip. The performance of a semiconductor is independent of wafer size. Since 2002, the largest wafers in full production have been 300 millimeters in diameter.

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[7] Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, vol. 38, no. 8 (April 19, 1965). Also see Gordon E. Moore, *Proceedings of the IEEE*, vol. 86, no. 1 (January 1998), at https://www.cs.utexas.edu/~fussell/courses/cs352h/papers/moore.pdf.

[8] Dylan Tweney, "April 19, 1965: How Do You Like It? Moore, Moore, Moore," *Wired*, April 19, 2010, and David Rotman, "We're Not Prepared for the End of Moore's Law," *MIT Technology Review*, February 24, 2020, at https://www.technologyreview.com/2020/02/24/905789/were-not-prepared-for-the-end-of-moores-law/.

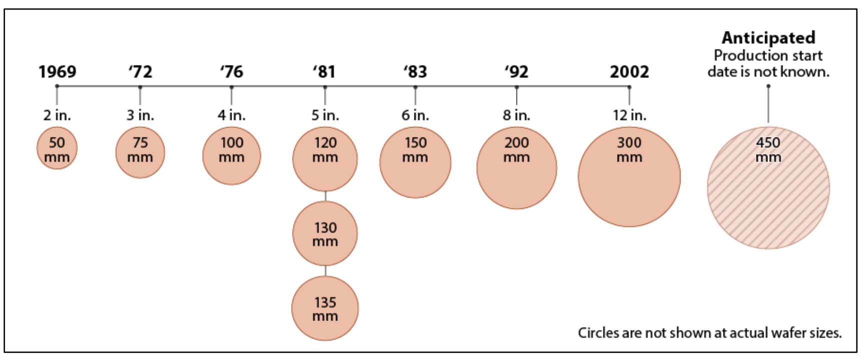
levels of research and investment spending. The increased power and decreased cost of semiconductors predicted by Moore's Law has created and revolutionized entire industries; a 2015 study estimated that advanced semiconductors played a critical role in enabling innovations that generated at least $3 trillion in incremental gross domestic product over the previous two decades.[9]

Semiconductor factories, also referred to as fabs or foundries, are often characterized by the size of the wafer that chips are printed on and the size of the transistor gate length printed on each chip (see box). Only a small number of firms have the capital to produce the most advanced semiconductors with reduced feature size, as the fabrication of each new generation of semiconductors requires more costly equipment and capital-intensive processes.[10] Leading-edge semiconductor manufacturers have to make concurrent R&D investments in development and support of multiple generations of chip technology.

Wafer Size

Semiconductor production lines primarily use 300-millimeter (mm) diameter wafers, also referred to as a 12-inch line (see **Figure 2**). In contrast, production lines built in the 1980s and 1990s used 6- and 8-inch (also referred to as 200mm diameter) wafers, and some older production lines still use 4-inch diameter wafers. As wafer diameter increases, more chips can be made from a single wafer, allowing the fixed costs of processing a wafer to be spread over a larger number of chips, thereby improving production efficiency and lowering the unit cost of the chips.[11] A 300mm wafer can yield more than 2,400 ICs, compared to the 1,000 ICs that can be made from a 200mm wafer.[12]

Figure 2. Evolution of Silicon Wafer Size



Source: CRS, modified from Evan Ramstad, "Why Computer-Chip Factories from the 1980s Are Still Going Strong in Bloomington," *StarTribune,* June 8, 2019.

[9] IHS (now IHS Markit), *Celebrating the 50th Anniversary of Moore's Law*, 2015, p. 9, at https://technology.informa.com/api/binary/532884.

[10] Rock's Law, which is sometimes referred to as Moore's second law, predicts that the cost of building next generation semiconductor chip fabrication plants will double every four years. John VerWey, *The Health and Competitiveness of the U.S. Semiconductor Manufacturing Equipment Industry*, USITC, Journal of International Commerce and Economics, July 2019, Office of Industries, Working Paper ID-058, p. 17, at https://www.usitc.gov/publications/332/working_papers/id_058_the_health_and_competitiveness_of_the_sme_industry_final_070219checked.pdf.

[11] OECD, *Measuring Distortions in International Markets: The Semiconductor Value Chain*, November 21, 2019, p. 20.

[12] Angelo Zino and Jia Yi Young, *Semiconductors and Semiconductor Equipment*, CFRA, May 2020, p. 37.

Each reduction in feature size is considered a move to a new generation of manufacturing technology. Some features of chips are now under 10nm,[13] a few chip producers have reached 5nm.[14] Some companies have announced plans to move to even smaller nodes.

Most semiconductors are made using 300mm wafers. Efforts to develop 450mm wafers have proven unsuccessful so far. The impetus for moving to larger wafers is the potential for decreased costs resulting from the production of more chips from a single wafer over the same time period. Delays in an industry shift to 450mm appear to be attributable to several factors: the challenge of getting equipment manufacturers, chip fabricators, and other elements of the supply chain to move forward together in such a shift; the potentially higher cost of new fabrication facilities and manufacturing equipment; and the industries' current investments (i.e., sunk costs) in existing facilities. Another factor in the decision to move to 450mm is the complexity of timing to align best with broader market conditions. One high-profile industry consortium formed in 2011 to develop 450mm wafer production—the Global 450 Consortium, whose founders included Intel, Samsung, GlobalFoundries, TSMC, IBM, and the College of Nanoscale Science and Engineering at the State University of New York Polytechnic Institute—disbanded in 2017.[15]

Feature Size

The most advanced chips today may have more than a trillion transistors. This miniaturization has led to feature sizes so small that performance can be impeded by electrons jumping out of their barriers (known as "leakage current") due to a phenomenon known as quantum tunneling. Reducing leakage current to allow even tighter packing of transistors is a focus of semiconductor research.[16]

The Global Semiconductor Industry

U.S.-headquartered semiconductor firms were responsible for the largest share (47%) of the $412 billion global market in 2019, as measured by sales.[17] Although their sales are higher now than in 2012, U.S.-headquartered companies' aggregate share of global sales has been falling, from 51.8% in 2012 to 46.8% in 2019 (see **Figure 3**). These data are based on the headquarters

[13] According to a U.S. International Trade Commission (USITC) analysis, currently "leading-edge chips" are those with a feature size of 14nm or below (for comparison, a human hair is about 75,000nm in diameter). The USITC also points out over the last two decades more companies are focused on producing "state of practice" chips with a feature size of 32nm-65nm and "legacy chips" with a feature size from 65nm to 10,000nm. See John VerWey, *Chinese Semiconductor Industrial Policy: Past and Present*, USITC, Journal of International Commerce and Economics, July 2019, p. 4, at https://www.usitc.gov/publications/332/journals/chinese_semiconductor_industrial_policy_past_and_present_jice_july_2019.pdf.

[14] Samsung, "Samsung Electronics Announces Second Quarter 2020 Results," press release, July 30, 2020, https://news.samsung.com/global/samsung-electronics-announces-second-quarter-2020-results; TSMC, website, "5nm Technology," at https://www.tsmc.com/english/dedicatedFoundry/technology/5nm.htm.

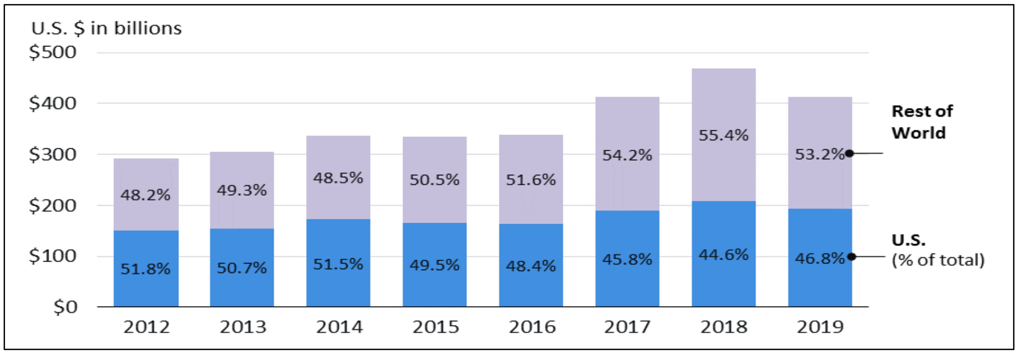
[15] Joel Hruska, "450mm Silicon Wafers Aren't Happening Any Time Soon as Major Consortium Collapses," *ExtremeTech*, January 13, 2017, at https://www.extremetech.com/computing/242699-450mm-silicon-wafers-arent-happening-time-soon-major-consortium-collapses.

[16] For differing opinions on the future prospects of silicon-based semiconductors, see "The Impact of Moore's Law Ending," *Semiconductor Engineering*, October 29, 2018, at https://semiengineering.com/the-impact-of-moores-law-ending/, and Bret Swanson, *Moore's Law at 50: The Performance and Prospects of the Exponential Economy*, American Enterprise Institute, November 2015, pp. 14-15, at https://www.innovationnj.net/news/moores-law-at-50-the-performance-and-prospects-of-the-exponential-economy.

[17] Global and U.S. industry sales represent sales of chips to a downstream customer or end-user.

location of the companies that that design and own the chips, which is not necessarily the company that physically produces the chip.

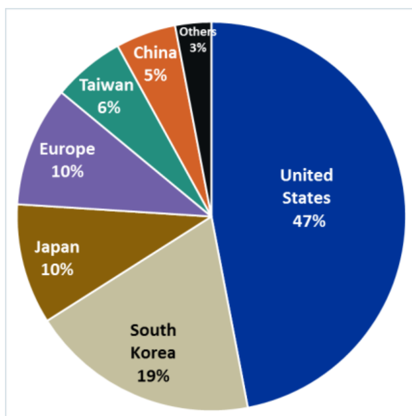
Figure 3. Worldwide and U.S. Semiconductor Industry Sales



Source: Semiconductor Industry Association (SIA), *2020 Databook*, p. 11.

Figure 4 shows global semiconductor market share in 2019, based on headquarters location. By this metric, the United States leads, followed by South Korea (19%), Japan (10%), Europe (10%), Taiwan (6%), and China (5%).[18] Semiconductor industry experts anticipate the U.S. share of worldwide sales to remain below 50% in 2020.

Figure 4. Global Semiconductor Industry Market Share, by Sales, 2019



Source: SIA, *2020 State of the U.S. Semiconductor Industry*, p. 7.

Notes: Sales based on the location of company headquarters.

As shown in **Appendix B**, six of the 15 largest semiconductor firms worldwide by sales in 2019 are headquartered in the United States: Intel, Micron Technology, Broadcom, Qualcomm, Texas Instruments, and Nvidia.[19] Not all of these firms own manufacturing facilities.[20] They draw on an extensive base of suppliers located in many countries. The Semiconductor Industry Association

[18] Semiconductor Industry Association (SIA), *2020 Factbook*, April 23, 2020, p. 3, at https://www.semiconductors.org/the-2020-sia-factbook-your-source-for-semiconductor-industry-data/.

[19] IC Insights, "Intel to Reclaim Number One Semiconductor Supplier Ranking in 2019," November 18, 2019, at https://www.icinsights.com/news/bulletins/Intel-To-Reclaim-Number-One-Semiconductor-Supplier-Ranking-In-2019—/.

[20] Additionally, some companies, such as Apple Inc., design semiconductors for their own use but contract for their manufacturing. Such firms are generally not classified as semiconductor manufacturers in government or industry data.

(SIA), the principal industry trade group, reported in 2016 that one large U.S.-based semiconductor firm had more than 16,000 suppliers worldwide, of which 7,300 were located in the United States.[21] In addition, in 2020, there are signs of additional industry consolidation across national borders and industry segments.

Semiconductor Market Segments

Semiconductors can be classified into four major product groups, mainly based on their function: microprocessors and logic devices; memory; analog; and optoelectronics, sensors, and discretes. Some of these products have broad functionality; others are designed for specific uses. According to SIA, the first two product groups account for two-thirds of global sales.

1. **Microprocessors and logic devices** are used for the interchange and manipulation of data in computers, communication devices, and consumer electronics.[22] They perform a wide variety of tasks, such as running a word processing program or a video game. Microprocessors and logic devices accounted for 42% ($171 billion) of total semiconductor sales.[23]
2. **Memory devices** are used to 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, smartphones, tablets, and flash memory, which retains data even when power is shut off. Memory devices accounted for 25% ($106 billion) of semiconductor sales.
3. **Analog devices** are used to translate analog signals, such as light, touch, and voice, into digital signals. For example, they are used to convert the analog sound of a musical performance into a digital recording stored online or on a compact disc. Analog devices accounted for about 13% ($54 billion) of semiconductor sales.
4. **Optoelectronics, sensors, and discretes (commonly referred to as O-S-D).** Optoelectornics and sensors are mainly used for generating or sensing light, for example, in traffic lights or cameras. Discretes—such as transistors, diodes, and resistors—contain only one device per chip and are designed to perform a single electrical function.[24]

Many chip manufacturers specialize in specific types of semiconductors. For example, the primary market for U.S.-based Intel Corporation, the largest global semiconductor manufacturer by sales in 2019 (see **Appendix B**), is microprocessors for the personal computer industry. Microprocessors are more difficult to manufacture, more technologically advanced, and more expensive than other semiconductor products. Intel's main competition in microprocessors is its considerably smaller rival, U.S.-headquartered Advanced Micro Devices (AMD).[25]

[21] SIA, *Beyond Borders: The Global Semiconductor Value Chain*, May 2016, p. 3, at https://www.semiconductors.org/wp-content/uploads/2018/06/SIA-Beyond-Borders-Report-FINAL-June-7.pdf.

[22] Angelo Zino and Jia Yi Young, *Industry Surveys Semiconductors and Semiconductor Equipment*, CFRA, May 2020, p. 35.

[23] CRS combined the global semiconductor sales data for microprocessors and logic devices (an older category of chips that are now widely considered a type of microprocessor) as reported in SIA's annual *Factbook*. Global semiconductor sales figures are from the World Semiconductor Trade Statistics.

[24] SIA, *2020 Factbook*, April 23, 2020, p. 11.

[25] Investopedia, "Who are Intel's (INTC) Main Competitors?," March 31, 2020, at https://www.investopedia.com/ask/

South Korean manufacturers Samsung and SK Hynix and U.S.-based Micron together accounted for 95% of global DRAM sales in 2019.[26] Micron was the fifth-largest semiconductor company in the world by sales in 2019 (see **Appendix B**). In recent years, these companies' heavy dependence on the DRAM market has been a challenge, as memory chips are considered commodities with little differentiation among them and typically with smaller profit margins than microprocessors.[27] In addition, DRAMs have been marked by boom and bust cycles, which have at times led to dramatic reductions in prices due to weak demand or excess capacity.[28]

Although semiconductor sales are dominated by large companies, a number of small semiconductor firms focus on specialized needs. According to some 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.[29] For example, Skywater Technology, a firm that Cypress Semiconductor spun off in 2017, and that Infineon acquired in 2020, operates a single small fab in Minnesota.[30] It is currently the only U.S.-owned pure-play semiconductor foundry[31] in the country, and operates as a trusted manufacturer (see "DOD Trusted Foundry Program") for the military's microelectronics program.[32] The Department of Defense announced that it would invest up to $170 million to increase Skywater's production of semiconductors designed with security-related aims, such as the ability to withstand radiation in space.[33]

Global Semiconductor Production

As semiconductors become smaller and are more densely packed with transistors, the complexity of manufacturing increases. **Figure 5** depicts a simplified graphic of the semiconductor production process that captures the main parts of the production stream.

answers/120114/who-are-intels-intc-main-competitors.asp.

[26] Statistica, *DRAM Chip Market Share by Manufacturer Worldwide from 2011 to 2019*, March 3, 2020, at https://www.statista.com/statistics/271726/global-market-share-held-by-dram-chip-vendors-since-2010/.

[27] Angelo Zino and Jia Yi Young, *Industry Surveys Semiconductors and Semiconductor Equipment*, CFRA, May 2020, pp. 41-42.

[28] "Micron, Samsung, and SK Hynix: The DRAM Oligopoly," *Seeking Alpha*, May 12, 2020, at https://seekingalpha.com/article/4346547-micron-samsung-and-sk-hynix-dram-oligopoly.

[29] First Research, *Semiconductor and Other Electronic Component Manufacturing*, April 27, 2020, at http://www.firstresearch.com/Industry-Research/Semiconductor-and-Other-Electronic-Component-Manufacturing.html.

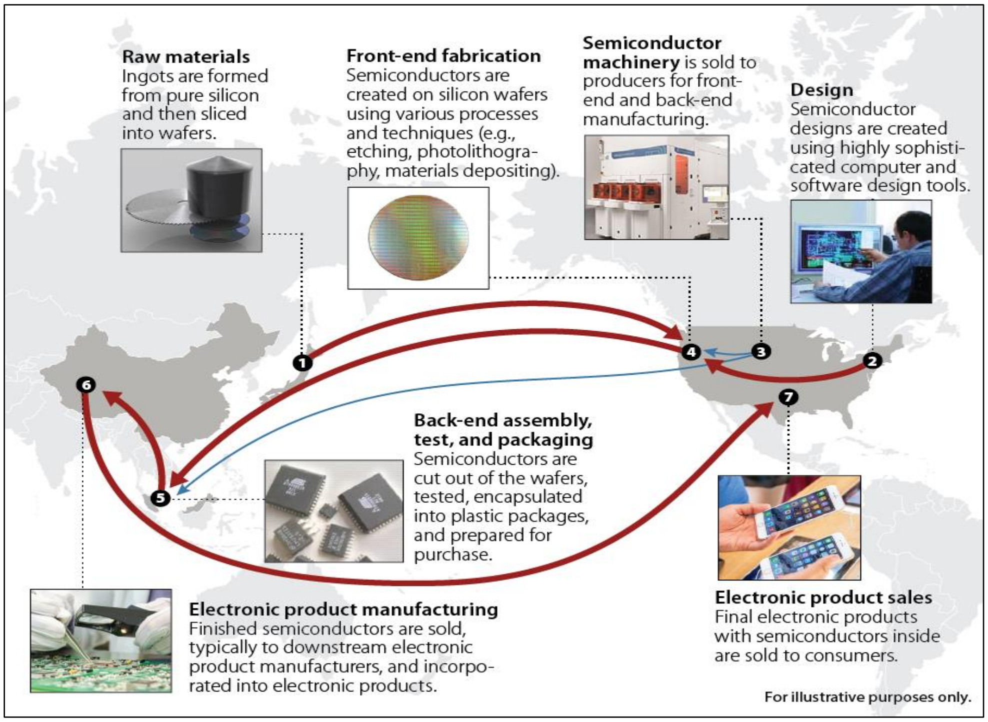
[30] Cypress Semiconductor, "Cypress Closes Sale of Minnesota Wafer Fabrication Facility," press release, March 1, 2017, at https://www.cypress.com/news/cypress-closes-sale-minnesota-wafer-fabrication-facility; and Infineon, "Infineon Technologies AG Completes Acquisition of Cypress Semiconductor Corporation, press release, April 16, 2020, at https://www.infineon.com/cms/en/about-infineon/press/press-releases/2020/INFXX202004-049.html.

[31] A pure-play semiconductor company engages in contract manufacturing of semiconductors for design firms, but produces no (or few) products of its own design.

[32] Samuel K. Moore, "The Foundry at the Heart of DARPA's Plan to Let Old Fabs Beat New Ones," *IEEE Spectrum*, August 6, 2018, at https://spectrum.ieee.org/nanoclast/semiconductors/processors/the-foundry-at-the-heart-of-darpas-plan-to-let-old-fabs-beat-new-ones.

[33] Carrigan Miller, "Behind Skywater's Chip-Plant Expansion, a $170M Pentagon Deal," *Minneapolis/St. Paul Business Journal*, October 21, 2019, at https://www.bizjournals.com/twincities/news/2019/10/21/behind-skywaters-chip-plant-expansion-a-170m.html.

Figure 5. Typical Global Semiconductor Production Pattern



Source: CRS, adapted from information provided by SIA.

Materials Used for Wafer Manufacturing

Silicon is still the most widely used basic material on which semiconductors are fabricated. Five firms account for 90% of the world's silicon wafer production; two Japanese firms, Shin-Etsu and Sumco, account for around 60%.[34] Silicon wafers are manufactured in a number of countries around the world, including the United States, Japan, Taiwan, Malaysia, and the United Kingdom.

In addition to silicon-based semiconductors, chips referred to as "III-V" semiconductors are cut from wafers made from a combination of one or more elements each from groups III and V on the periodic table, such as gallium arsenide (GaAs), silicon carbide (SiC), and gallium nitride (GaN).[35] These materials are most often used in the manufacture of photovoltaics (e.g., solar cells), light-emitting diodes (LEDs), sensors, optoelectronics, and other products.

III-V semiconductors are generally characterized by a wide bandgap,[36] which offers a variety of improved performance characteristics over silicon. According to the U.S. Department of Energy (DOE):

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[34] Siltronic, *Siltroni-A Leading Producer of Silicon Wafer, Factbook, Investor Relations, August 2020*, p. 4, at https://www.siltronic.com/en/investors/reports-and-presentations.html.

[35] A more recent numbering system for element groups in the periodic table, recommended by the International Union of Pure and Applied Chemistry (IUPAC), labels groups III and V as groups 13 and 15, but the term "III-V" is most widely used for this class of semiconductor materials.

[36] The bandgap is the energy difference between the valence band and the conduction band of a solid material. No electronic state can exist between these bands. Wide bandgap materials permit devices to operate at much higher voltages, frequencies, and temperatures.

> Wide bandgap semiconductor materials allow power electronic components to be smaller, faster, more reliable, and more efficient than their silicon-based counterparts. These capabilities make it possible to reduce weight, volume, and life-cycle costs in a wide range of power applications. Harnessing these capabilities can lead to dramatic energy savings in industrial processing and consumer appliances, accelerate widespread use of electric vehicles and fuel cells, and help integrate renewable energy onto the electric grid.[37]

Other advantages of III-V semiconductors, which vary among the different types, include radiation resistance (especially important to the defense, space, and nuclear energy sectors); operation at higher voltages, frequencies, and temperatures; higher processing speeds; faster switching speeds with lower transition losses; higher power density; and higher material strength.[38]

The DOE Office of Energy Efficiency and Renewable Energy supports research on III-V semiconductors, and sponsors the PowerAmerica Manufacturing USA institute (see "Current Federal R&D Efforts" for more information on PowerAmerica).

Design; Fabrication; and Assembly, Testing, and Packaging

Semiconductor manufacturing has three distinct components. Some companies specialize in a particular component, while others engage in two or three.

1. **Design**, in which companies conceive new products and specifications to meet customer needs and reduce these ideas to particular logic and circuit designs for manufacture;
2. **Front-end fabrication**, in which fabs are used to manufacture semiconductors by etching microscopic electronic circuits onto wafers of silicon (or, less commonly, other materials); and
3. **Back-end assembly, testing, and packaging (ATP)**, in which wafers are sliced into individual semiconductors, encased in plastic, and put through a quality-control process.

Front-end fabrication and back-end ATP both require highly specialized machinery. SIA estimates that 90% of the value of a semiconductor chip is split evenly between the design and fabrication stages, while the remaining 10% is added during the ATP stage.[39]

Companies that design semiconductors may or may not have their own foundries to make chips. An integrated device manufacturer (IDM) conducts chip design, fabrication, and ATP in-house. IDMs include Intel, Samsung, SK Hynix, Micron, Texas Instruments, Toshiba, Sony, STMicroelectronics, Infineon, and NXP. Some IDMs also provide contract fabrication services for other firms. A fabless firm, by contrast, engages solely in chip design and partners with a

[37] DOE, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, "Wide Bandgap Semiconductors: Pursuing the Promise," at https://www1.eere.energy.gov/manufacturing/rd/pdfs/wide_bandgap_semiconductors_factsheet.pdf.

[38] DOE, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, "Wide Bandgap Semiconductors: Pursuing the Promise"; Applied Materials, "Wide Band Gap—The Revolution in Power Semiconductors," at http://www.appliedmaterials.com/nanochip/nanochip-fab-solutions/april-2019/wide-band-gap; and Texas Instruments, "Advantages of Wide Band Gap Materials in Power Electronics—Part 1," at https://e2e.ti.com/blogs_/b/powerhouse/archive/2016/05/24/advantages-of-wide-band-gap-materials-in-power-electronics-part-1.

[39] John VerWey, *Global Value Chains: Explaining U.S. Bilateral Trade Deficits in Semiconductors*, USITC, Executive Briefing on Trade, March 2018, p. 1, at https://www.usitc.gov/publications/332/executive_briefings/ebot-semiconductor_gvc_final.pdf.

contract foundry (a foundry that typically has limited or no semiconductor design capability) to manufacture a design into chips. "Fab-lite" semiconductor companies, such as Infineon, maintain some in-house fabrication production, but contract a significant amount of chip production to outside foundries.

Design

According to the research firm Trendforce, seven of the top 10 fabless semiconductor design firms, by revenue, are headquartered in the United States—including the top three (Broadcom, Qualcomm, and Nvidia); three are headquartered in Taiwan.[40] In 2020, Nvidia bid to acquire ARM—a United Kingdom-headquartered company acquired by Japan's SoftBank in September 2016—potentially adding to U.S.-headquartered design capabilities.[41]

Fabless semiconductor firms generally have higher and less volatile profit margins than semiconductor manufacturers with integrated operations.[42] Among the risks faced by fabless firms are quality control and ensuring timely production when demand for outside foundries' capacity is strong. The number of fabless design companies is increasing as some IDMs choose to become fabless and new companies enter the market.[43] For some U.S. policymakers, the reliance of U.S. fabless firms on merchant foundries in East Asia to produce chips has raised national security concerns (such as increased risks of concentration by geography and among a small number of companies, the possibility of intellectual property loss due to the need to share details of chip design and production with foundries, assured access to production capacity, and control of product integrity), especially as it relates to leading-edge, 7nm-and-below chip production. According to a report produced for the U.S. Air Force in 2019, "Close to 90% of all high-volume, leading-edge IC production will soon be based in Taiwan, [China], and South Korea, with the U.S. share of global IC fab capacity falling to 8% by 2022, down from 40% in the 1990s."[44]

There is competition in semiconductor design focused on unique functions. These include chip design for personal computers (including memory chips), video and graphic processing and display, servers, tablets, cellphones, automobiles, digital televisions, set-top boxes, game consoles, medical devices, wearable systems, wireless networks, military systems, and other industrial applications. Some of these chips may also incorporate artificial intelligence to varying degrees.

Figure 6, produced by market research firm IC Insights in 2017, shows estimated 2017 revenues for selected IC end-use markets, the share of global revenues for each in 2017 (on the y-axis), and the projected compound annual growth rate for revenues from 2016 to 2021 (on the x-axis). ICs for cell phones and personal computers (PCs) were the two largest segments, together accounting for more than 40% of global IC revenues. The two segments with the fastest projected compound

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[40] TrendForce, "Global Top 10 IC Designers' 2019 Revenues Drop by 4.1% YoY, as Industry Growth to Face Challenges from Covid-19 Pandemic in 2020, Says TrendForce," press release, March 17, 2020, at https://press.trendforce.com/node/view/3341.html.

[41] Nvidia, *Nvidia to Acquire ARM for $40 Billion, Creating World's Premiere Computing Company for the Age of AI,* September 13, 2020, at https://nvidianews.nvidia.com/news/nvidia-to-acquire-arm-for-40-billion-creating-worlds-premier-computing-company-for-the-age-of-ai.

[42] Angelo Zino and Jien Loon Choong, *Semiconductors and Semiconductor Equipment*, CFRA Industry Surveys November 2019, p. 31.

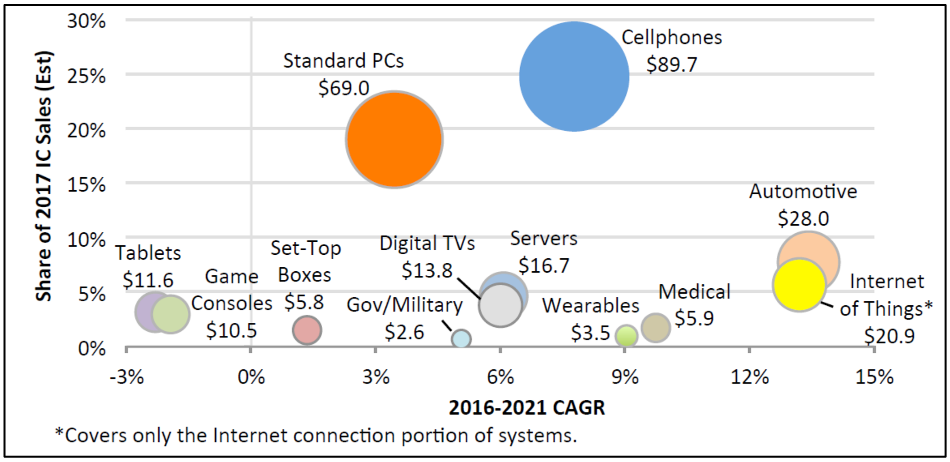
[43] Angelo Zino and Jia Yi Young, *Semiconductors and Semiconductor Equipment*, CFRA, May 2020, p. 25.

[44] Rick Switzer, *U.S. National Security Implications of Microelectronics Supply Chain Concentrations in Taiwan, South Korea, and the People's Republic of China,* p. 4, September 2019, as prepared for the U.S. Air Force, Office of Commercial and Economic Analysis.

annual growth rate (CAGR) for revenues during the 2016 to 2021 period were automotive (13.4% CAGR) and IoT (13.2% CAGR). The CAGR for all IC revenues for this period was 7.9%, growing from $297.7 billion in 2016 to a projected $434.5 billion in 2021.[45] Likely areas of growth beyond 2021 include automotive and IoT. These market shares and growth rates pertain only to a portion of the entire IC market.

Figure 6. Integrated Circuit End-Use Markets and Estimated Growth Rates

Dollars in billions



Source: IC Insights, *Research Bulletin, Automotive and IoT Will Drive IC Growth Through 2021*, December 6, 2017, provided to CRS by IC Insights in email communication, August 27, 2020.

Notes: Data for 2017 based on estimated sales. Compound annual growth rates (CAGR) for 2016-2021 based on 2016 sales and projected sales for 2021.

Beyond fabless design firms and IDMs, competitors in these markets include companies in other industries. Facebook designs chips optimized for the types of content it stores and processes on its servers. Apple develops chips for the iPhone and the iPad. Automakers are working with partners to develop chips that support electric and hybrid-electric vehicles, as well as to support autonomous driving functions. In each case, the physical production of the custom-designed chips is performed by contract foundries.

Semiconductor designers often rely on other companies for IP cores[46] and electronic design automation (EDA) software.[47] Designers work with foundries to ensure that their designs can be reliably manufactured.[48] Fabless firms work in close coordination with contract fabs. For example:

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[45] IC Insights, *Research Bulletin, Automotive and IoT Will Drive IC Growth Through 2021*, December 6, 2017, provided to CRS by IC Insights in email communication, August 27, 2020.

[46] An intellectual property (IP) core is a reusable component of design logic with a defined interface and behavior. Arm Holdings is the largest company that sells and licenses IP cores. Nvidia is in talks to acquire ARM. (George Leopold, "Nvidia Said to be Close on Arm Deal," *HPC Wire*, August 3, 2020, at https://www.hpcwire.com/2020/08/03/nvidia-said-to-be-close-on-arm-deal/.)

[47] EDA firms make the specialized software that is used to design all semiconductor devices. The three largest EDA companies are Cadence (U.S.), Synopsys (U.S.), and Mentor Graphics (Germany).

[48] McKinsey & Company, *Semiconductor Design and Manufacturing: Achieving Leading-Edge Capabilities*, August 20, 2020, p. 4, at https://www.mckinsey.com/industries/advanced-electronics/our-insights/semiconductor-design-and-manufacturing-achieving-leading-edge-capabilities.

> Xilinx [a fabless firm] and UMC [a contract fab] pioneered the "virtual IDM" relationship, where the fabless company has full access to the process technology and is an active development partner. Xilinx and UMC worked together to develop the process technology, create test chips, and so on. In fact, Xilinx had a whole floor of one of UMC's buildings for their own employees.[49]

This relationship involves high levels of cooperation and information sharing which can potentially increase the risk of IP loss. A variety of tools (e.g., contracts, non-disclosure agreements, encryption) are used to prevent the unauthorized sharing of this information.

Fabrication: Facilities (Foundries)

Semiconductor foundries, which conduct the front-end manufacturing process, are capital-intensive operations. High capital costs create barriers to entry. Although estimates vary, industry experts say that a new semiconductor factory, much of which may be obsolete after five or six years, now costs at least $7 billion to build, with some asserting that an advanced chip fab can cost as much as $20 billion.[50] According to SIA, the majority of initial fab construction costs is in the production of semiconductor manufacturing equipment, with some pieces costing more than $100 million each.[51]

Because semiconductor manufacturers have high fixed costs and continuing requirements for factory improvements, they require high capacity utilization to remain profitable. Moreover, fabs generally require retooling every few years, again involving significant costs. Between 2010 and 2018, the U.S. semiconductor manufacturing industry's domestic expenditures for new plants and equipment ranged from $11 billion to $22 billion.[52] Capital expenditures approached 20% of the value of industry shipments in 2018, compared to approximately 4% for the manufacturing sector as a whole.[53]

Other challenges for the industry include the rapid obsolescence of chips in inventory as improved designs displace existing products, potentially leaving producers with unsalable inventories and financial losses, as well as the high cost of R&D associated with the development of next generation chips (see "Industry R&D Spending").

TSMC, headquartered in Taiwan, operates the world's largest foundry and is the world's largest contract chipmaker.[54] TSMC is one of only three manufacturers in the world that fabricate the

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[49] Daniel Nenni and Paul McLellan, *Fabless: The Transformation of the Semiconductor Industry*, 2019 Revised Edition, p. 60, SemiWiki.com.

[50] James A. Lewis, *Learning the Superior Techniques of the Barbarians: China's Pursuit of Semiconductor Independence*, Center for Strategic and International Studies, January 2019, p. 11, at https://csis-prod.s3.amazonaws.com/s3fs-public/publication/190115_Lewis_Semiconductor_v6.pdf.

[51] Conversation between CRS and SIA, June 5, 2020.

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

[53] Industry shipments based on NAICS 3344 from *Annual Survey of Manufactures: Summary Statistics for Industry Groups and Industries in the U.S.: 2018*, at https://www.census.gov/programs-surveys/asm/data/tables.html. Capital expenditures are taken from the U.S. Census Bureau's *Annual Capital Expenditures Survey*, at http://www.census.gov/programs-surveys/aces.html.

[54] TSMC makes tailor-made products for clients, unlike companies such as Samsung and Intel, which reserve a segment of their fabrication production for their own products. TSMC is an important source of semiconductor chips for a number of U.S. and Chinese tech firms, including Apple, Qualcomm, Broadcom, Nvidia, Huawei, and Xilinx. TSMC also makes high-performance chips designed by Xilinx for U.S. military equipment, which in turn are used in F-35 fighter jets and satellites.

most advanced semiconductor chips—those containing transistors of 10nm or smaller. The other two are Samsung and Intel. TSMC recently announced that it intends to build a $12 billion semiconductor fabrication plant in Arizona, where it initially plans to manufacture 5nm-class chips.[55] The Arizona facility would be TSMC's second manufacturing site in the United States; the company operates an older 200mm fab in Camas, WA, where it primarily manufactures flash memory.[56] It also has design centers in Austin, TX, and San Jose, CA.[57] The majority of TSMC's production is in Taiwan, where it operates three 300mm fabs capable of producing more than 100,000 printed wafers per month[58] at the 90nm to 7nm nodes.[59] The company also has a fab in Nanjing, China.

If TSMC proceeds with its announced plan to build a fab in Arizona, the wafers it produces are expected to be at least 7% more expensive to manufacture than if they were made in Taiwan or China, according to one assessment of the project. The differential is attributed to the planned facility's relatively small capacity as well as to higher construction, labor, and utility costs.[60] Some in Congress have raised questions about this project, flagging potential national security concerns about reliance on a foreign-headquartered producer, and potentially yet-to-be-disclosed tax breaks, licensures, and other incentives offered as an inducement to construct the new TSMC plant in the United States.[61]

Fabrication: Equipment and Other Suppliers

Key suppliers to foundries include the makers of the equipment, tools, and software used in the fabrication of semiconductors, as well as wafer producers. In the fabrication process,[62] which may take two months, designs are 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 a small number of manufacturers. Five equipment suppliers accounted for more than three-fourths of worldwide sales in 2018.[63] Of the five, Applied Materials, Lam Research Corporation, and KLA Corporation are headquartered in the United States. The other two are the Dutch company ASML[64] and the Japanese firm Tokyo Electronics. Chinese companies make about 2% of the

[55] TSMC says it expects to start construction in 2021, with production to begin in 2024. (TSMC, "TSMC Announces Intention to Build and Operate an Advanced Semiconductor Fab in the United States," press release, May 15, 2020, https://www.tsmc.com/tsmcdotcom/PRListingNewsArchivesAction.do?action=detail&newsid=THGOANPGTH.)

[56] Joel Hruska, "TSMC Will Build 5NM Chip Foundry in Arizona," *ExtremeTech*, May 18, 2020, at https://www.extremetech.com/computing/310646-tsmc-will-build-5nm-chip-foundry-in-arizona.

[57] For the locations of TSMC fabs, see https://www.tsmc.com/english/contact_us.htm#TSMC_fabs.

[58] TSMC, *TSMC Annual Report 2019*, p. 77, at https://www.tsmc.com/english/investorRelations/annual_reports.htm. Some say "gigafab" sites reduce construction costs by about 25% versus building a single stand-alone fab.

[59] TSMC, *GIGAFAB Facilities*, at https://www.tsmc.com/english/dedicatedFoundry/manufacturing/gigafab.htm.

[60] Scotten Jones, "Cost Analysis of the Proposed TSMC US Fab," *SemiWiki.com*, May 15, 2020, at https://semiwiki.com/semiconductor-manufacturers/tsmc/285846-cost-analysis-of-the-proposed-tsmc-us-fab/.

[61] Letter from The Honorable Charles E. Schumer, United States Senator; The Honorable Patrick Leahy, United States Senator; and Jack Reed, United States Senator, to The Honorable Wilbur Ross and The Honorable Mark Esper, Secretary of Commerce and Secretary of Defense, May 19, 2020.

[62] Angelo Zino and Jia Yi Young, *Semiconductors and Semiconductor Equipment*, CFRA, May 2020, pp. 35-36. The slicing of wafers to create semiconductors takes place in highly automated clean rooms, which must be kept free of all airborne matter, because the circuitry on a chip is so small that even microscopic particles can make it unusable. Human presence is minimized in the clean room, and production workers wear "bunny suits" that cover the entire body.

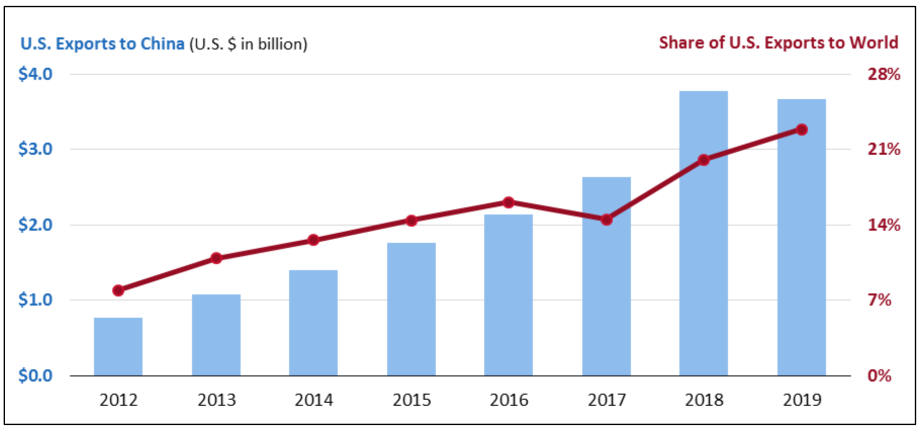
[63] Statista, *Global Market Share Held by Semiconductor Equipment Manufacturers from 1Q'17 to 2018*, March 2, 2020, at https://www.statista.com/statistics/267392/market-share-of-semiconductor-equipment-manufacturers/.

[64] ASML is the sole provider of the most advanced photolithography technology—extreme ultraviolet

world's semiconductor fabrication and test equipment.[65] Chinese semiconductor companies are mostly dependent on U.S. and other non-Chinese suppliers at this time and some industry experts assess that China is unlikely to have a viable indigenous equipment industry for at least a decade due to technical gaps.[66] Conversely, the three leading U.S.-headquartered semiconductor equipment firms depend on overseas sales, including sales to China, for roughly 90% of their revenue.[67]

Since the introduction of China's semiconductor policy in 2014, U.S. exports of semiconductor equipment to China have increased three-fold (see **Figure 7**). China's access to U.S. semiconductor equipment has become a focus of U.S. government attention because it is seen to contribute importantly to the development of China's semiconductor industry. Since May 2020, the Department of Commerce (DOC) has amended rules to restrict the sale of chips that are fabricated using any U.S. design software or technology, which includes EDA software tools and equipment used in overseas fabs, to Huawei Technologies Co. and its affiliates.[68] This restriction does not currently apply to other Chinese firms, however.

Figure 7. U.S. Exports to China, Share of U.S. Exports to the World of Semiconductor Fabrication Equipment



Source: CRS, compiled from U.S. Census Bureau data.

Notes: Data for North American Industry Classification System (NAICS) Code 333242 (semiconductor machinery manufacturing).

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photolithography—used to make state-of-the-art 5nm node chips, a technology not yet in mass production.

[65] Saif M. Kahn and Carrick Flynn, *Maintaining China's Dependence on Democracies for Advanced Computer Chips*, Brookings Institution in collaboration with Center for Security and Emerging Technology, April 2020, p. 4, at https://www.brookings.edu/research/maintaining-chinas-dependence-on-democracies-for-advanced-computer-chips/.

[66] Saif M. Khan, *Maintaining the AI Chip Competitive Advantage of the United States and its Allies*, Center for Security and Emerging Technology, CSET Issue Brief, December 2019, p. 4.

[67] John VerWey, *The Health and Competitiveness of the U.S. Semiconductor Manufacturing Equipment Industry*, USITC, Working Paper ID-058, July 2019, p. 5.

[68] Bureau of Industry and Security (BIS), "Commerce Addresses Huawei's Efforts to Undermine Entity List, Restricts Products Designed and Produced with U.S. Technologies," press release, May 15, 2020, at https://www.commerce.gov/news/press-releases/2020/05/commerce-addresses-huaweis-efforts-undermine-entity-list-restricts; and BIS, interim final rule and request for comments, "Export Administration Regulations: Amendments to General Prohibition Three (Foreign-Produced Direct Product Rule) and the Entity List," 85 *Federal Register* 29849, May 19, 2020, at https://www.federalregister.gov/documents/2020/05/19/2020-10856/export-administration-regulations-amendments-to-general-prohibition-three-foreign-produced-direct.

Assembly, Testing, and Packaging

In back-end production, chips are assembled into finished semiconductor components and tested to verify that they function as intended, prior to assembly and packaging for incorporation into finished products (e.g., smartphones). This stage of the manufacturing process is the most labor-intensive and is often performed in countries where wages are comparatively low, such as Malaysia, Vietnam, and the Philippines. Back-end production is frequently outsourced to specialist packaging companies. It was the first function to be outsourced because it had been the lowest value additive stage of semiconductor production. More recently, ATP has become more advanced and sensitive in the semiconductor supply chain with increased functionality embedded in chips.[69]

Key Parts of the Global Semiconductor Supply Chain

Figure 8 illustrates the share of revenues accounted for by companies headquartered in each location for four different segments: IDMs, fabless firms, contract foundries, and outsourced ATP. U.S.-based firms lead in IDM and fabless firm revenues, while Taiwanese firms lead in contract foundry and outsourced ATP revenues.

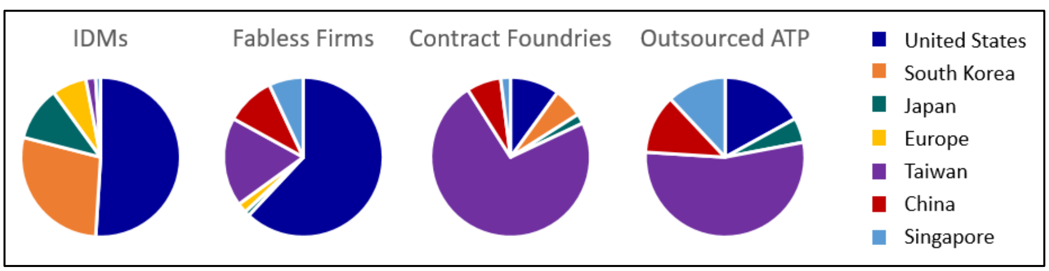
IDMs: U.S.-based firms account for 51% of total global IDM revenues, followed by firms based in South Korea (28%), Japan (11%), Europe (7%), Taiwan (2%), and Singapore (1%).

Fabless Firms: U.S.-based firms account for 62% of total global fabless firm revenues, followed by Taiwan (18%), China (10%), Singapore (7%), Europe (2%), and Japan (1%).[70]

Contract Foundries: Taiwan-based firms account for 73% of total global contract foundry revenues, followed by firms based in the United States (10%), China (7%), South Korea (6%), Japan (2%), and Singapore (2%).

Outsourced ATP: Firms based in Taiwan account for 54% of total outsourced ATP revenues, followed by firms based in the United States (17%), China (12%), Singapore (12%), and Japan (5%).[71]

Figure 8. Revenue for Value Chain Segments by Headquarters Location, 2018



Source: CRS, from data presented in Seamus Grimes and Debin Du, "China's Emerging Role in the Global Semiconductor Value Chain," *Telecommunications Policy*, April 18, 2020, https://www.sciencedirect.com/science/article/pii/S0308596120300513.

[69] John VerWey, *Global Value Chains: Explaining U.S. Bilateral Trade Deficits in Semiconductors*, USITC, Executive Briefing on Trade, p. 2, March 2018.

[70] It is unclear from the source data as to whether the value of chips designed by non-semiconductor firms (e.g., Apple) are included in these calculations.

[71] Seamus Grimes and Debin Du, "China's Emerging Role in the Global Semiconductor Value Chain," *Telecommunications Policy,* April 18, 2020, https://www.sciencedirect.com/science/article/pii/S0308596120300513.

Notes: The source document uses the term Outsourced Semiconductor Assembly Test (OSAT); CRS uses the term Outsourced ATP consistent with the earlier taxonomy.

Global Semiconductor Fabrication Capacity

While actual production *outputs* are proprietary and generally confidential, production *capacities* are well known and used as the primary metric for assessing where semiconductors are made.[72] Close to 90% of worldwide 300mm equivalent fab capacity is now located outside the United States (see **Table 1**).

In 2019, North America (primarily the United States) ranked fifth in semiconductor fabrication capacity, accounting for 11% of worldwide capacity, down from 13% in 2015.[73] South Korea ranked first, followed by Taiwan, Japan, and China; China's share grew from 8% in 2015 to 12% in 2019.[74] (See **Table 1**.) It is important to note that this ranking does not consider the technical characteristics of each country's semiconductor production; a wafer used to produce old-generation memory chips counts the same as one used to make a leading-edge semiconductor.

Table 1. Semiconductor Fabrication Capacity

300mm Equivalent Wafer Capacity by Country/Region, 2015 and 2019

Country/Region	2015	2019
South Korea	26%	28%
Taiwan	24%	22%
Japan	18%	16%
China	8%	12%
North America	13%	11%
Europe	3%	3%
Rest of World (ROW)	9%	7%

Source: IC Insights, Global Wafer Capacity 2020-2024.

The U.S. Semiconductor Manufacturing Industry

Nationally, about 730 firms located in the United States were involved in semiconductor and related device manufacturing in 2017, based on the latest data available, down from about 820 firms in 2013.[75] This reduction in the number of firms appears to be due in large part to industry consolidation. The U.S. semiconductor industry's contribution to the U.S. economy measured by value added was $29.9 billion in 2018, accounting for approximately 1% of U.S. manufacturing

[72] Some consulting firms may offer this data for a fee.

[73] Rankings based on 300mm equivalent wafer capacity. Data from fabs using other than 300mm wafers has been normalized to allow for comparison. Data based on physical location of fabrication facility, not location of company headquarters.

[74] IC Insights, *Global Wafer Capacity 2020-2024*, February 13, 2020, p. 1, at https://www.icinsights.com/services/global-wafer-capacity/report-contents/.

[75] U.S. Census Bureau, *Statistics of U.S. Businesses*, 2017 and 2013, based on semiconductor and related device manufacturing, which is captured in the North American Industry Classification System (NAICS) code 334413, at http://www.census.gov/econ/susb/.

value added.[76] Manufacturers continue to produce more powerful chips with greater functionality while reducing the cost per unit of computing power.

Industry R&D Spending

The need for large investments in developing new manufacturing technologies and chip designs means that semiconductor companies spend far more on research and development than manufacturers in general. In 2016, R&D as a share of domestic sales was 11.6% for U.S. semiconductor manufacturers and 20.3% for semiconductor machinery manufacturers,[77] compared to 5.4% for all U.S. manufacturing industries. Intel, the largest U.S.-based chipmaker, spent $13.4 billion on R&D in 2019, an amount equal to 19% of worldwide sales.[78] According to SIA, industry-wide investment rates in R&D have ranged between 15% and 20% of sales over the past decade, and they have remained consistently high regardless of annual trends in sales.[79]

Due to their heavy R&D spending, semiconductor companies regularly rank among the top U.S. corporate patent recipients, measured by number of patents granted. In 2019, this list included Intel (3,020), Qualcomm (2,348), and Micron Technology (1,266).[80]

Semiconductor Manufacturing Jobs

In the United States, three states (California, Texas, and Oregon) together account for more than half of the sector's employment.[81] California accounted for more than one-fifth of all domestic semiconductor manufacturing jobs in 2019 (for other states in the top 10, see **Table 2**).[82] According to the U.S. Bureau of Labor Statistics (BLS), the semiconductor and related device manufacturing industry located in the United States, regardless of ownership, directly employed 184,600 workers in 2019, 107,500 fewer jobs (-37%) than in 2001. In part, this employment decline may be attributable to a combination of automation and offshoring away from the United States and towards the Asia-Pacific region.[83] However, the BLS employment estimate is not comprehensive. It does not include workers employed by the growing number of fabless semiconductor establishments, which are treated for statistical purposes as part of the wholesale trade sector rather than the manufacturing sector. Neither the BLS estimate nor the SIA estimate

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

[77] NSF, "Domestic R&D Paid by the Company and Others and Performed by the Company as a Percentage of Domestic Net Sales, by Industry and Company Size: 2016," Table 18, *Business Research and Development Innovation: 2016*, May 13, 2019, at https://ncses.nsf.gov/pubs/nsf19318/#&.

[78] Securities and Exchange Commission (SEC), EDGAR System, Intel Corporation, 10-K filing, January 24, 2020, at https://www.sec.gov/Archives/edgar/data/50863/000005086320000011/a12282019q410kdocumentcourte.pdf.

[79] SIA, *2020 Factbook*, April 23, 2020, pp. 17-18.

[80] U.S. Patent and Trademark Office, *All Technologies Report*, granted January 1, 1995-December 31, 2019, March 2020, at https://www.uspto.gov/web/offices/ac/ido/oeip/taf/h_at.htm.

[81] See SIA's website for a U.S. map showing the locations of commercial semiconductor manufacturing facilities, at https://www.semiconductors.org/semiconductors-101/industry-impact/.

[82] CRS review of state employment data are from the BLS Quarterly Census of Employment and Wages (QCEW) program.

[83] CRS analysis of employment data from the BLS QCEW for NAICS code 334413, at https://data.bls.gov/cew/apps/table_maker/v4/table_maker.htm#type=0&year=2019&qtr=A&own=5&ind=334413&supp=0. 2019 data are preliminary.

counts workers in other industries who may be engaged in designing semiconductors for their own firm's use.

Semiconductor production represented 1.4% of total U.S. manufacturing employment in 2019. The semiconductor manufacturing workforce earned an average of $166,400 in 2019, more than twice the average for all U.S. manufacturing workers ($69,928).[84]

Table 2. Top 10 States in Semiconductor Manufacturing Employment

	2019 Semiconductor Manufacturing Employment	% of U.S. Semiconductor Manufacturing Employment Total
California	42,211	23%
Texas	29,218	16%
Oregon	26,894	15%
Arizona	19,272	10%
Florida	8,613	5%
Idaho	8,214	4%
Massachusetts	8,114	4%
New York	6,822	4%
North Carolina	5,283	3%
Washington	3,320	2%
Top 10 States Total	**157,961**	**86%**
United States Total	**184,632**	**100%**

Source: CRS analysis of data from U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment and Wages, accessed July 2020.

Notes: Semiconductor manufacturing employment data cover NAICS codes 334413 (semiconductor and related device manufacturing).

Another 22,753 workers, earning an average pay of $161,339, were engaged in 2019 in the manufacturing of equipment used to make semiconductors.[85] The equipment industry has added more than 7,000 jobs since 2011 due to strong growth in revenue, which rose from $13.7 billion in 2011 to $20.2 billion in 2019.[86]

Semiconductor Production in the United States

Six semiconductor companies currently manufacture 300mm silicon wafers at 20 fabs in the United States (**Table 3**). These fabs are located in eight states, with the largest number in Texas

[84] CRS analysis of average wage data are from the BLS QCEW program.

[85] CRS analysis of BLS QCEW data for NAICS code 333242 (semiconductor machinery manufacturing), at https://data.bls.gov/cew/apps/table_maker/v4/table_maker.htm#type=0&year=2019&qtr=A&own=5&ind=333242&supp=0.

[86] Griffin Holcomb, *Semiconductor Machinery Manufacturing in the US*, IBISWorld, Electric Connection: Advancement in Technology Have Boosted Industry Performance, August 2020, p. 50, at https://www.ibisworld.com/united-states/market-research-reports/semiconductor-machinery-manufacturing-industry/.

(5), Oregon (4), and New York (3). U.S.-headquartered semiconductor companies conduct more than half of their front-end wafer processing operations in the United States.

To attract, grow, and retain semiconductor manufacturing, the federal government and some U.S. states offer tax incentives, grants, low-cost loans, free land, and other incentives that influence corporate decisions on where to build capacity. These policies help to defray the billions of dollars of a plant's cost over its useful life. Such policies remain controversial.

A recent example of state support is a $500 million grant from New York's Empire State Development Corporation to Cree Inc. to build a $1 billion silicon carbide wafer factory in Marcy, NY, along with $100 million to prepare the site for construction.[87] New York has also agreed to provide up to $17.5 million in grants for ON Semiconductor's purchase of the GlobalFoundries factory in East Fishkill, NY, as well as $22.5 million in tax credits. [88] Controversy has arisen over federal and state subsidies for TSMC's planned new facility in Arizona, intended to offset the higher costs of building and operating a fab in the United States.[89]

U.S.-headquartered semiconductor manufacturers have both domestic and global production facilities.

- Intel fabricates more than half of its wafers in the United States at facilities in Arizona, New Mexico, and Oregon. It also operates fabs in Ireland, Israel, and China.[90]
- Micron Technology has fabs in Idaho, Utah, and Virginia, as well as in Singapore, Japan, and Taiwan.[91]
- Texas Instruments operates fabs in Texas and Maine, and it is constructing a new fab in Richardson, TX. The company also has manufacturing facilities in China, Taiwan, Malaysia, and the Philippines.[92]
- GlobalFoundries, a company based in California and owned by Abu Dhabi's sovereign wealth fund, has acquired U.S.-based fabs formerly owned by AMD

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[87] Liz Young, "State Approves $500 Million Grant to Cree for Upstate Factory," *Albany Business Review*, November 22, 2019, at https://www.bizjournals.com/albany/news/2019/11/22/esd-cree-factory-marcy-utica-grant.html. Also see New York State, "Governor Cuomo Announces $1 Billion Public-Private Partnership with Cree Creating World's Largest Silicon Carbide Device Facility at the March Nanocenter," press release, September 23, 2019, at https://www.governor.ny.gov/news/governor-cuomo-announces-1-billion-public-private-partnership-cree-creating-worlds-largest.

[88] ON Semiconductor, "ON Semiconductor and GlobalFoundries Partner to Transfer Ownership of East Fishkill, NY 300mm Facility," press release, April 22, 2019, at https://www.globalfoundries.com/news-events/press-releases/semiconductor-and-globalfoundries-partner-transfer-ownership-east; and Governor Andrew M. Cuomo, "Governor Cuomo Announces Agreement with ON Semiconductor to Acquire and Preserve GlobalFoundries Fabrication Plant in Hudson Valley," press release, April 22, 2019, at https://www.governor.ny.gov/news/governor-cuomo-announces-agreement-semiconductor-acquire-and-preserve-globalfoundries.

[89] Debby Wu, "TSMC Scores Subsidies and Picks Sites for $12 Billion U.S. Plant," *Bloomberg*, June 8, 2020, at https://www.bloomberg.com/news/articles/2020-06-09/tsmc-confident-of-replacing-any-huawei-orders-lost-to-u-s-curbs.

[90] Securities and Exchange Commission, EDGAR System, Intel Corporation, 10-K filing, at https://www.sec.gov/ix?doc=/Archives/edgar/data/50863/000005086320000011/a12282019q4-10kdocument.htm. See also Intel, "Helping Maintain Industry Leadership and Driving Innovation," at https://www.intel.com/content/www/us/en/architecture-and-technology/global-manufacturing.html.

[91] Micron Technology, 10-K Annual Report, October 17, 2019, p. 27, at http://investors.micron.com/.

[92] Texas Instruments, 2019 Annual Report, pp. 6 and 13, at https://investor.ti.com/financial-information/earnings-annual-reports. Also see Peter Clarke, "TI Tips Site for Next 300mm Analog Wafer Fab," eeNews, April 22, 2019, at https://www.eenewsanalog.com/news/ti-tips-site-next-300mm-analog-wafer-fab.

and IBM Corporation. In addition, the company operates fabs in Germany and Singapore; in 2019, it halted plans for its $10 billion 12nm logic fab in Chengdu, China.[93]

Some firms and fabs produce semiconductors at various feature sizes, also known as technology nodes. For example, Intel produces at the 65nm node down to the 7nm node and Global Foundries produces at the 90nm node down to the 12nm node.

Table 3. 300mm (12-inch) Semiconductor Fabs in the United States, 2019

Company	Number of Fabs	Location	Products
GlobalFoundries	2	Malta, NY	Foundry/Dedicated
GlobalFoundries	1	East Fishkill, NY	Foundry/Dedicated
Intel Corporation	2	Chandler, AZ	Logic/Microprocessor Unit (MPU)
Intel Corporation	4	Hillsboro, OR	Logic/MPU
Intel Corporation	2	Albuquerque, NM	Logic/MPU
Micron Technology	1	Boise, ID	R&D/Pilot Projects
Micron Technology	1	Lehi, UT	Memory/Flash
Micron Technology	2	Manassas, VA	Memory/DRAM
Samsung	2	Austin, TX	Foundry/IDM
Skorpios	1	Austin, TX	Fab/Pilot
Texas Instruments	1	Richardson, TX	Analog/Linear
Texas Instruments	1	Dallas, TX	Analog/Mixed Signal

Source: CRS, with data provided by Semiconductor Equipment and Materials International (SEMI) a trade group that represents global semiconductor equipment and material suppliers, on May 6, 2020, from its priority Fab Construction Monitor database.

U.S. semiconductor manufacturing capacity has been stable for many years, but most new and advanced capacity is located overseas. Due, in large part, to Chinese government investments, over half of new fabs to be opened over the next several years are projected to be in China. According to the industry group Semiconductor Equipment and Materials International (SEMI), construction is planned to begin on 27 new fab projects in 2020 and 2021. Of these, 3 are to be located in the United States, while 14 are to be located in China. The other projects are to be located in Taiwan (5), Southeast Asia (2), Europe (2), and South Korea (1).[94]

[93] Sidney Leng, "US Semiconductor Giant Shuts China Factory Hailed as a Miracle, in Blow to Beijing's Chip Plans," *South China Morning Post*, May 20, 2020, at https://www.scmp.com/economy/china-economy/article/3085230/us-semiconductor-giant-shuts-china-factory-hailed-miracle.

[94] Email communication between CRS and SEMI, May 6, 2020.

The Global Semiconductor Landscape

The semiconductor industry is highly globalized. Global trade in semiconductors and electronics involves cross-border design and manufacturing processes. The rise of the fabless semiconductor production model has accelerated the outsourcing of production, often to offshore foundries. Negotiation of the World Trade Organization (WTO) International Trade Agreement (ITA) in 1996, and the addition of ITA II in 2015, have brought semiconductor-related tariffs close to zero in many countries, further facilitating the globalization of the supply chain.[95]

Trade data provide a partial picture of the manufacturing process, and can overstate or understate the roles of different countries in the semiconductor supply chain. For example, during the production process, chips are frequently imported, processed in some way, and then re-exported several times before being incorporated into a final product. In 2019, more than 40% of U.S. semiconductor imports were then re-exported.[96] Thus, while Malaysia accounted for more than 40% of U.S. semiconductor imports in 2019, Malaysia's contribution to those products is primarily post-production assembly, packaging, and testing of semiconductors made in other countries.

Because of limitations in the ability of trade data to capture the complexity of the supply chain, the U.S. industry uses global sales as a metric for market share. According to SIA, U.S.-headquartered companies accounted for 47% of global sales in 2019; foreign markets accounted for 82% of

Semiconductors and Intellectual Property

Semiconductor R&D investments provide competitive advantage by enabling the production of more powerful and functional chips and by reducing their costs. The knowledge generated by these investments is protected as intellectual property rights (IPR), which includes patents, copyrights, and trade secrets, among other things.

IPR is central to the value and operation of semiconductor companies. Patents, for example, allow the owner to produce unique products or use unique manufacturing processes, or to license their use to others for compensation. Thus, semiconductor companies seek to protect their IPR from countries, companies, and others that would improperly or illegally acquire and use it. IPR also incentivizes further investments in R&D that enable continuing improvements.

IPR enforcement is a particular challenge for the semiconductor industry because of the global nature of the supply chain and companies' dependence on global compliance with IP laws and practices. Trade tools to protect IP and address patent infringement include the WTO and World Intellectual Property Organization provisions and commitments, as well as U.S. trade law, including Section 301 of the Trade Act of 1974 and Section 337 of the Tariff Act of 1930. The U.S. government has also negotiated specific IP commitments and protections in its free trade agreements. However, international enforcement efforts can be uncertain, costly, and time consuming.

In addition, much of a semiconductor company's tacit knowledge resides in its employees, who may be subject to the recruitment efforts of other companies and countries. Counterfeit chips are also a recognized problem in the semiconductor industry. The consequences of a counterfeit semiconductor can cause costly failures in a wide range of consumer, health, transportation, and military systems.

For further information, see CRS Report RL34292, *Intellectual Property Rights and International Trade*, by Shayerah Ilias Akhtar, Ian F. Fergusson, and Liana Wong.

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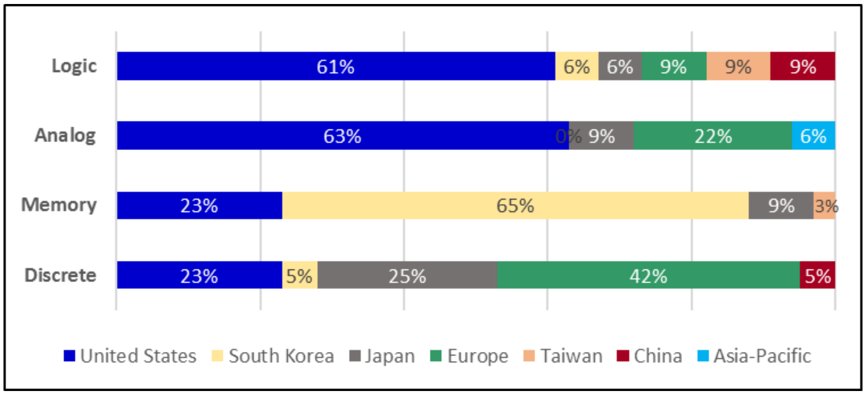
95 In July 2015, the WTO expanded the Information Technology Agreement (ITA), first signed in 1996, which has more than 80 signatories, including the United States. Beginning on July 1, 2016, the signatories agreed to immediately eliminate some tariffs and then phase out others by January 2024, on 201 information technology products not included in the original 1996 ITA. China is a signatory to both agreements, but still has high tariffs on certain products. Mexico, a substantial location for electronics assembly that incorporates finished semiconductors in electronic goods, is not party to the agreements.

96 Re-exports refer to export of goods that were originally imported but then minimally processed before being exported.

these sales.[97] The U.S. Bureau of Economic Analysis reports that approximately 75% of the production by foreign affiliates of U.S. parents in the semiconductor industry is sold outside of the United States.[98]

Figure 9 shows market share by the location of company headquarters for each major semiconductor market.

Figure 9. Semiconductor Industry Market Share, by Sales, 2019



Source: CRS, based on SIA, *2020 State of the U.S. Semiconductor Industry*, p. 8.

The following sections discuss semiconductor activities around the world.

East Asia

Semiconductor fabrication is concentrated in Japan, South Korea, Taiwan, and Singapore; China is discussed later in this report. In addition to locally owned companies, some U.S.-headquartered firms operate fabs in the region. For example, Micron operates three major plants in Singapore along with a fab in Taiwan and one in Japan.[99]

Since the early 1990s, Japan-headquartered companies' share of the global semiconductor market has fallen significantly. Several Japan-headquartered companies have closed fabs in Japan, and some have gone bankrupt. In 2019, only two Japanese chipmakers—Kioxia (formerly Toshiba)[100] and Sony—ranked among the top 15 semiconductor firms worldwide as ranked by sales (see **Appendix B**).

As the market positions of Japanese companies have declined, companies based elsewhere in East Asia have become prominent global manufacturers, mostly in the DRAM segment of the market. South Korea's Samsung Electronics and SK Hynix were the second- and fourth-largest semiconductor companies in the world in 2019. According to data from Statistica, an industry statistics portal, Samsung held 43.5% of the global DRAM market in 2019, followed by SK

[97] SIA, Trade, at https://www.semiconductors.org/policies/trade/. Also see SIA, *Beyond Borders: The Global Semiconductor Value Chain*, June 15, 2018.

[98] Bureau of Economic Analysis (BEA), U.S. Direct Investment Abroad, Activities of U.S. Multinational Enterprises, 2017 preliminary statistics (accessed July 30, 2020). Table II.H.2, at https://www.bea.gov/worldwide-activities-us-multinational-enterprises-preliminary-2017-statistics.

[99] Micron, 10-K Annual Report, October 17, 2019, p. 27, at http://investors.micron.com/.

[100] In 2018, Toshiba was sold to Bain consortium, which includes SK Hynix, Apple, Dell, Seagate, and Kingston. Its name was changed to Kioxia.

Hynix at 29.2%. U.S.-headquartered Micron held 22.3% of the market.[101] To preserve its global competitiveness, especially with respect to TSMC and Intel, Samsung has begun building a leading-edge production line in South Korea to produce chips at 5nm and below.[102] The growth of the South Korean semiconductor industry has been nurtured by government funding and the financial backing of some of the large, family-controlled industrial conglomerates known as chaebols that play a central role in South Korea's economy.[103] To bolster its fabless sector, in 2019, the South Korean government announced that it would invest approximately $860 million by 2030 in the production of next-generation semiconductors for future industries.[104]

Taiwan has become the world's leading location for semiconductor foundry manufacturing (as discussed in the section "Fabrication: Facilities (Foundries)." Taiwan's semiconductor foundry industry is dominated by two contract manufacturers, TSMC and UMC.[105] In 2019, TSMC had about three times the production capacity of UMC.[106] 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.[107] This concentration of semiconductor manufacturing has become a concern to some U.S. policymakers due to the risks associated with potential supply disruptions due to trade, geopolitical, and other considerations. In August 2020, TSMC announced a 2nm R&D center and confirmed plans for a 3nm foundry in Taiwan.[108] TSMC has said that some of its research will focus on material alternatives to silicon.[109] The Taiwan government is likely supporting these investments as part of broader efforts to promote advanced technology R&D and manufacturing in Taiwan.[110] By structuring the investment as an R&D center, TSMC would qualify for government support.[111]

Singapore has also developed a government-supported semiconductor industry by providing public funds and tax incentives to firms constructing fabs there. Unlike Japan, South Korea, and Taiwan, Singapore's strategy has been to build a semiconductor industry through foreign direct

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[101] Statistica, The Statistics Portal, "Global DRAM Chip Vendors' Market Share 2011-2019," March 3, 2020, at https://www.statista.com/statistics/271726/global-market-share-held-by-dram-chip-vendors-since-2010/.

[102] Samsung, "Samsung Electronics Expands Its Foundry Capacity with a New Production Line in Pyeongtaek, Korea," press release, May 21, 2020, at https://news.samsung.com/global/samsung-electronics-expands-its-foundry-capacity-with-a-new-production-line-in-pyeongtaek-korea.

[103] Eleanor Albert, *South Korea's Chaebol Challenge*, Council on Foreign Relations, May 4, 2018, at https://www.cfr.org/backgrounder/south-koreas-chaebol-challenge.

[104] South Korea, "Remarks by President Moon Jae-in at Ceremony to Unveil System Semiconductor Vision," press release, April 30, 2019, at https://english1.president.go.kr/BriefingSpeeches/Speeches/590.

[105] Taiwan Semiconductor Industry Association, *Overview of Taiwan Semiconductor Industry*, 2019, p. 9, at https://www.tsia.org.tw/EN/PublOverview?nodeID=60.

[106] IC Insights, "Five Semiconductor Companies Hold 53% of Global Wafer Capacity," press release, February 13, 2020, at https://www.icinsights.com/news/bulletins/Five-Semiconductor-Companies-Hold-53-Of-Global-Wafer-Capacity/.

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

[108] Lisa Wang, "TSMC Developing 2 nm Tech at New R&D Center," *Taipei Times*, August 26, 2020, at https://taipeitimes.com/News/front/archives/2020/08/26/2003742295.

[109] Ramish Zafar, "TSMC Rejects Production in US and Starts Research on Materials Beyond Silicon," WCCF Tech, November 3, 2019, at https://wccftech.com/tsmc-us-manufacturing-silicon/.

[110] See CRS In Focus IF10256, *U.S.-Taiwan Trade Relations*, by Karen M. Sutter.

[111] Ministry of Economic Affairs, Taiwan, *Taiwan Key Innovative Industry: Semiconductors*, March 2018, at https://www.roc-taiwan.org/uploads/sites/30/2018/03/Semiconductors.pdf. Taiwan's Advanced Technology Research Plan offers to cover 40% to 50% of total development funding for new technology not yet mature in Taiwan that will generate strategic products, services, or industries.

investment by global companies, such as Micron and GlobalFoundries.[112] It has no indigenous semiconductor firm.

China

China accounts for 60% of global demand for semiconductors—in large part due to the concentration of global consumer electronics production there—but it has played a limited role to date in chip production.[113] More than 90% of the semiconductors China uses are either imported or made domestically by foreign chipmakers.[114] In 2019, 24 of the 126 300mm wafer fabrication plants in operation worldwide were located in China, according to SEMI (see **Table 4**).[115] Chinese-headquartered companies' IC products are generally less technologically advanced than those of companies headquartered in other countries, whereas the most advanced fab production in China is performed by non-Chinese firms.[116] Intel, Samsung, and TSMC are among the major global semiconductor firms that operate fabrication facilities in China.[117]

Chinese firms, such as Semiconductor Manufacturing International Corporation (SMIC), appear to be advancing their capabilities in part due to collaboration with foreign companies. China continues to attract global industry collaboration with the pull of government financing, leading to the expansion of China's fabrication capacity. Market research firm IC Insights forecasts that at least half of semiconductor production in China in 2023 will come from foreign-controlled fabs, with the balance coming from Chinese fabs.[118]

Table 4. Worldwide 300mm Semiconductor Fab Count

Number of Operating Fabs by Country or Region

Country/Region	2015	2017	2019
Taiwan	29	34	36
United States	18	20	20
South Korea	13	17	19
Japan	10	11	13

[112] John A. Matthew, "A Silicon Island of the East: Creating a Semiconductor Industry in Singapore," *California Management Review*, vol. 41, no. 2 (Winter 1999), at https://journals.sagepub.com/doi/pdf/10.2307/41165986.

[113] "China's Semiconductor Industry: 60% of the Global Semiconductor Consumption," Daxue Consulting, March 26, 2020, at https://daxueconsulting.com/chinas-semiconductor-industry/; Yi-ting Wang, "Chip War: Taiwan's Role in China's Semiconductor Industry Policy" (Dissertation, University of Trier, 2019), p. 4, at https://cdn.website-editor.net/b6f182e46cf54e88940dc05258b375a9/files/uploaded/CGI2_Wang_2019_Chip%2520War.pdf; and Mark Lapedus, "China: Fab Boom or Bust?," *Semiengineering*," March 16, 2017, at https://semiengineering.com/china-fab-boom-or-bust/.

[114] Matthew Fluco, *Betting All the Chips: China Seeks to Build a World-Class Semiconductor Industry*, CKGSB Knowledge, November 29, 2018, at https://knowledge.ckgsb.edu.cn/2018/11/29/technology/china-semiconductor-industry/.

[115] SEMI is an industry association of materials, design, equipment, software, devices, and services companies supplying the semiconductor industry. The organization was formerly known as Semiconductor Equipment and Materials International. SEMI, "Count of Facilities in Operation," provided to CRS on May 1, 2020.

[116] Sisi Chen, *Integrated Circuit Manufacturing in China*, IBISWorld, Industry Report 5043, July 2019, p. 18, at https://www.ibisworld.com/china/market-research-reports/integrated-circuit-manufacturing-industry/.

[117] John VerWey, *Chinese Semiconductor Industrial Policy: Prospects for Future Success*, USITC, August 2019, p. 21.

[118] David Manners, "China IC Production Growing 15% CAGR 2018-2023," February 8, 2019, at https://www.electronicsweekly.com/news/business/china-ic-production-growing-15-cagr-2018-2023-2019-02/.

Country/Region	2015	2017	2019
China	8	12	24
Europe & Mideast	7	8	8
Southeast Asia	5	7	6
Total	**90**	**109**	**126**

Source: SEMI Worldwide Fab Forecast, May 2020.

Two decades ago, China designated semiconductors as a strategic sector, committing to develop a vertically integrated domestic semiconductor industry through policies such as government subsidies and tax incentives.[119] Since 2006, the Chinese government has advanced more ambitious policies to reduce its reliance on foreign technology and become self-sufficient in strategic emerging industries as part of a broader effort to develop its economy. It seeks to accomplish this primarily by acquiring intellectual property and know-how from foreign competitors in support of the stated goal of eventually trying to displace them.[120]

In June 2014, the Chinese government 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."[121] The document included measures to support an aggressive growth strategy, with the goal of meeting 70% of China's semiconductor demand from domestic production by 2025.[122] In 2019, China revised the goal upward, setting an objective of expanding its domestic production of semiconductors (including from foreign firms in China) to meet 80% of domestic demand by 2030, as part of its *Made in China 2025* industrial strategy.[123] In August 2020, the Chinese government updated its semiconductor policy to emphasize foreign academic and industry collaboration (including domestic and overseas R&D centers), expanding China's role in developing international rules for protection of intellectual property, advancing Chinese standards, use of antitrust authorities, and priority financing vehicles (e.g., local governments, insurance and asset management companies, corporate bond issuances, and stock market listings).[124] According to the Office of the United States Trade Representative, "China's strategy calls for creating a closed-loop semiconductor manufacturing ecosystem with self-sufficiency at every stage of the manufacturing process—from IC design and manufacturing to packaging and testing, and the production of related materials and equipment."[125]

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[119] Alexander Chipman Koty, "Chips All In: Investing in China's Semiconductor Industry," *China Briefing*, March 2, 2016, at https://www.china-briefing.com/news/chips-all-in-investing-in-chinas-semiconductor-industry/.

[120] Cong Cao, Richard P. Suttmeier, and Denis Fred Simon, "China's 15-Year Science and Technology Plan," *Physics Today*, 59 (12), 2006.

[121] 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, at https://legacy.trade.gov/topmarkets/semiconductors.asp.

[122] "Chips on their Shoulders," *The Economist*, January 23, 2016, at https://www.economist.com/business/2016/01/23/chips-on-their-shoulders.

[123] *Made in China 2025* is a highly detailed 10-year "guide for China's manufacturing strategy" to "transform China into the global manufacturing leader before the centennial of the founding of New China." The report identifies scores of principles, policies, and programs China believes will enable the achievement of the goals outlined in the report.

[124] China State Council, "Notice on Issuing Several Policies to Promote the High-Quality Development of the Integrated Circuit Industry and the Software Industry in the New Period," Guofa (2020) 8, August 4, 2020.

[125] Office of the United States Trade Representative (USTR), *Section 301 Report*, March 22, 2018, p. 113, at

China's semiconductor policies feature a substantial government role in directing and financing Chinese businesses to obtain foreign intellectual property related to semiconductors. The Chinese government uses production targets; subsidies; tax preferences; trade and investment barriers (including pressure to engage in joint ventures); and discriminatory antitrust, IP, procurement, and standards practices.[126] The policies seek to leverage China's central role in global microelectronics manufacturing and potential as a semiconductor production hub to pressure foreign companies to localize production, share technology, and partner with the Chinese government and affiliated entities.

To implement its semiconductor plan, China created a government fund—the China Integrated Circuit Investment Industry Fund (CICIIF)—to channel an estimated $150 billion in state funding in support of domestic industry, overseas acquisitions, and the purchase of foreign semiconductor equipment.[127] In October 2019, China announced the creation of a second semiconductor fund with an estimated capitalization of $28.9 billion.[128] The fund or its affiliates often take direct equity stakes and board positions in the companies they finance.[129] The fund also provides state subsidies to import equipment and software tools, which can constitute up to half of a foundry's capital expenditures.[130] In 2018, SMIC, China's largest IC foundry, announced plans to establish a $255 million fund to make equity investments in semiconductors and related industries.[131] In May 2020, SMIC received an investment worth $2.2 billion from Chinese state investors.[132]

In 2019, the Organisation for Economic Co-operation and Development (OECD) found that Chinese semiconductor companies overwhelmingly benefitted from below-market government equity injections, as compared to other global firms.[133] The OECD concluded that the state role is

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https://ustr.gov/sites/default/files/Section%20301%20FINAL.PDF.

[126] See, for example, China's State Council, "Guideline for the Promotion of the Development of the National Integrated Circuit Industry," June 2014; China's State Council, "Notice on Issuing Several Policies to Promote the High-Quality Development of the Integrated Circuit Industry and the Software Industry in the New Period," Guofa (2020) 8, August 4, 2020; Center for International Governance Innovation, "Beyond 'Forced' Technology Transfers Analysis of and Recommendations on Intangible Economy Governance in China," CIGI Papers No. 239, March 2020, at https://www.cigionline.org/sites/default/files/documents/no239_2.pdf; John VerWey, "Chinese Semiconductor Industrial Policy: Past and Present," USITC, *Journal of International Commerce and Economics*, July 2019; and U.S. Chamber of Commerce, *Made in China 2025: Global Ambitions Built on Local Protections*, 2017, at https://www.uschamber.com/sites/default/files/final_made_in_china_2025_report_full.pdf.

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

[128] Yoko Kubota, "China Sets up New $29 Billion Semiconductor Fund," *Wall Street Journal*, October 25, 2019, at https://www.wsj.com/articles/china-sets-up-new-29-billion-semiconductor-fund-11572034480.

[129] Tianlei Huang, "Government-Guided Funds in China: Financing Vehicles for State Industrial Policy," China Economic Watch, Peterson Institute for International Economics, June 17, 2019, at https://www.piie.com/blogs/china-economic-watch/government-guided-funds-china-financing-vehicles-state-industrial-policy#_ftn2.

[130] OECD, Trade and Agricultural Directorate, Trade Committee, "Measuring Distortions in International Markets: The Semiconductor Value Chain," November 21, 2019, pp. 94-95.

[131] Yimian Wu, "China State-Owned CICIIF to Launch $255M Semiconductor Fund with Foundry," *China Money Network*, at https://www.chinamoneynetwork.com/2018/05/07/china-state-owned-ciciif-to-launch-255m-semiconductor-fund-with-foundry.

[132] Josh Horwitz, "China Semiconductor Fab SMIC Gets $2.2 bln Investment from Gov't Funds amid Global Chip Spat," Reuters, May 18, 2020, at https://www.reuters.com/article/china-semiconductor-smic/china-semiconductor-fab-smic-gets-22-bln-investment-from-govt-funds-amid-global-chip-spat-idUSL4N2D019Y.

[133] According to the OECD, "In particular, below-market equity in the sense of this report poses a formidable challenge to notification mechanisms given its lack of an internationally accepted definition (much less an estimation method). The consequences extend beyond trade and competition, however, as the lack of transparency on financial support

more pervasive in China's semiconductor industry than formal ownership reflects because of the opaque nature of shareholding and funding.[134]

Although China-headquartered manufacturers have made technological advances, they remain dependent in critical ways on foreign technology, know-how (such as foreign talent and collaboration), and global markets (such as acquisitions and foreign presence).[135] The market research company IC Insights predicts that China's domestic semiconductor production could meet 20% of China's demand by 2025—about one-third of the government's 70% target—and that at least half of this domestic production would come from foreign-operated facilities.[136] China's current market position has prompted some in industry to downplay the potential competitive threat that China poses and argue against further restrictions on U.S. semiconductor firms' activities in China.[137] Its continued dependence on foreign technology has also drawn attention to the ways in which U.S. industry ties are building China's capabilities.[138]

China has looked to joint ventures and foreign acquisitions to further its position in semiconductors. Leading U.S. technology firms with semiconductor-related expertise have partnered with or have invested in Chinese state firms tied to China's national semiconductor plan.[139] In fabrication, in 2015, Qualcomm and IMEC[140] established a joint R&D venture with SMIC and Huawei to support the Chinese firms' efforts to make 14nm logic chips.[141] Foreign acquisitions have positioned China in the advanced packaging market, including a 2015 CICIIF-funded acquisition of Singapore-based STATS ChipPac.[142] In 2016, China-headquartered Nantong Fujitsu took an 85% equity stake in AMD's packing and testing businesses in Malaysia and China. In 2015, Beijing E-Town Capital, a CICIIF shareholder, acquired U.S.-headquartered Mattson Technology, gaining specialized capabilities in etchers and rapid thermal processing

undermines government accountability and public oversight." (OECD (2019), "Measuring Distortions in International Markets: The Semiconductor Value Chain," OECD Trade Policy Papers, No. 234, p. 104, OECD Publishing, Paris, at https://doi.org/10.1787/8fe4491d-en.)

134 OECD (2019), "Measuring Distortions in International Markets: The Semiconductor Value Chain," OECD Trade Policy Papers, No. 234, OECD Publishing, Paris, at https://doi.org/10.1787/8fe4491d-en.

135 OECD, Trade and Agricultural Directorate, Trade Committee, "Measuring Distortions in International Markets: The Semiconductor Value Chain," November 21, 2019, p. 21.

136 IC Insights, "China to Fall Far Short of its "Made-in-China 2025" Goal for IC Devices," press release, May 21, 2020, at https://www.icinsights.com/news/bulletins/China-To-Fall-Far-Short-Of-Its-MadeinChina-2025-Goal-For-IC-Devices/.

137 See, for example, Antonio Varas and Raj Varadarajan, "How Restricting Trade with China Could End U.S. Semiconductor Leadership," Boston Consulting Group, March 9, 2020.

138 Saif M. Khan, *Maintaining the AI Chip Competitive Advantage of the United States and its Allies*, Center for Security and Emerging Technology, CSET Issue Brief, December 2019, p. 4.

139 John VerWey, *Chinese Semiconductor Industrial Policy: Past and Present*, USITC, Journal of International Commerce and Economics, July 2019, at https://www.usitc.gov/publications/332/journals/chinese_semiconductor_industrial_policy_past_and_present_jice_july_2019.pdf.

140 IMEC is the Belgium-based Interuniversity Microelectronics Centre, an international research and development organization focused on nanoelectronics and digital technologies.

141 "SMIC, Huawei, Imec, and Qualcomm in Joint Investment on SMIC's New Research and Development Company," SMIC, *PRNewswire*, June 23, 2016, at https://www.prnewswire.com/news-releases/smic-huawei-imec-and-qualcomm-in-joint-investment-on-smics-new-research-and-development-company-300103277.html.

142 Securities and Exchange Commission, EDGAR System, Semiconductor Manufacturing International Corporation, "Inside Information Announcement: Co-Investment Agreement and Investment Exit Agreement in Relation to Proposed Acquisition," December 22, 2014, at https://www.sec.gov/Archives/edgar/data/1267482/000130901415000021/exhibit1.htm; and Mark Lapedus, "Consolidation Hits OSAT Biz," *Semiconductor Engineering*, February 18, 2016, at https://semiengineering.com/consolidation-hits-osat-biz/.

equipment and strip tools used in semiconductor production.[143] In 2015, a CICIIF consortium acquired Integrated Silicon Solutions, Inc., and gained specialized chip expertise.[144]

For the last several years, the U.S. government has responded to U.S. industry's concerns by stepping up efforts to counter China's state-led industrial policies and certain trade and investment practices. Among other trade actions, the Trump Administration imposed tariffs on China under Section 301 of the Trade Act of 1974 (19 USC §§2411-2420) after finding that China's policies and practices related to forced technology transfer requirements, cyber-enabled theft of U.S. intellectual property and trade secrets, discriminatory and nonmarket licensing practices, and state-funded strategic acquisition of U.S. assets were unreasonable or discriminatory.[145]

In April 2018, the Trump Administration announced $50 billion in tariffs on products related to China's plans to develop indigenous industries, including semiconductors, under its flagship *Made in China 2025* initiative.[146] The Trump Administration has imposed an additional three rounds of tariffs; China has responded in kind with tariffs on U.S. goods. Under the Section 301 tariffs, a chip finished in China is subject to a U.S. import tariff of 25%, even if its components are made in the United States. Based on data compiled by SIA, close to a third of the Section 301 tariffs affect the semiconductor industry. In January 2020, the U.S. and Chinese governments signed a phase one trade deal to begin to address some concerns about protection of U.S.-based firms' intellectual property, but the agreement left most systemic concerns related to industrial policies and technology transfer to future talks.[147]

Moreover, the Department of Justice has moved to counter China's IP theft in semiconductors. In 2018, the Department of Justice charged a Chinese state-owned company, Fujian Jinhua Integrated Circuit, allegedly in concert with the Taiwan company United Microelectronics Company (UMC), for stealing technology for the manufacture of DRAM chips from Micron Technology.[148] In June 2020, a Taiwan court found three past and current UMC engineers guilty of stealing Micron's trade secrets. The engineers received sentences of 4.5 to 6.5 years and were fined between $135,000 and $200,000 each; the court fined UMC $3.4 million. UMC has said

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143 Securities and Exchange Commission, EDGAR System, at https://www.sec.gov/Archives/edgar/data/928421/000119312515392660/d46587dex992.htm; "Mattson Technology, Inc. Announces Completion of Acquisition by Beijing E-Town Dragon Semiconductor Industry Investment Center," Yahoo! Finance, https://finance.yahoo.com/news/mattson-technology-inc-announces-completion-131206198.html.

144 "GigaDevice to Merge with ISSI, Say Sources," *China Flash Market*, November 22, 2016, at https://en.chinaflashmarket.com/news/view?id=10677.

145 See CRS In Focus IF11346, *Section 301 of the Trade Act of 1974*, by Andres B. Schwarzenberg.

146 USTR, "Under Section 301 Action, USTR Releases Proposed Tariff List on Chinese Products," press release, April 3, 2018, at https://ustr.gov/about-us/policy-offices/press-office/press-releases/2018/april/under-section-301-action-ustr.

147 For further information, see CRS Insight IN11208, *U.S. Signs Phase One Trade Deal with China*, by Karen M. Sutter.

148 Department of Justice, "PRC State-Owned Company, Taiwan Company, and Three Individuals Charged with Economic Espionage," press release, November 1, 2018, at https://www.justice.gov/opa/pr/prc-state-owned-company-taiwan-company-and-three-individuals-charged-economic-espionage. The Department of Justice also announced a new initiative aimed at countering intellectual property theft from China. For more information, see "Attorney General Jeff Sessions Announces New Initiative to Combat Chinese Economic Espionage," press release, November 1, 2018, at https://www.justice.gov/opa/speech/attorney-general-jeff-sessions-announces-new-initiative-combat-chinese-economic-espionage.

that it is appealing the ruling.[149] The Department of Commerce sanctioned Fujian Jinhua by restricting its access to U.S. technology through U.S. export controls (discussed below).[150]

U.S. Controls on Semiconductors

In response to China's efforts to acquire U.S. advanced technologies and companies, the Trump Administration together with Congress has moved to tighten foreign investment reviews and licensing of dual-use technologies to China.

Reviews of Foreign Investments

Since 2015, the U.S. government's Committee on Foreign Investment in the United States (CFIUS) [151] has increased scrutiny of Chinese firms' bids to acquire leading U.S. semiconductor firms. Additionally, in 2018, Congress worked with the Trump Administration to strengthen CFIUS' foreign investment review authorities with the passage of the Foreign Investment Risk Review and Modernization Act (FIRRMA, P.L. 115-232), which strengthened CFIUS' foreign investment review authorities.[152]

There are several public examples of Chinese semiconductor transactions being blocked or being withdrawn after scrutiny by the U.S. government. (See **Table 5**.) In 2015, Tsinghua Unigroup, a Chinese state-controlled firm, proposed to acquire Micron Technology for $23 billion.[153] The proposed acquisition raised concerns among some Members of Congress and within the Obama Administration. The prospect of intense scrutiny of the transaction and the potential for CFIUS to recommend that the transaction be blocked on national security grounds likely resulted in the acquisition bid being abandoned. 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.[154] In

[149] Debby Wu, "Engineers Found Guilty of Stealing Micron Secrets for China," *Bloomberg*, June 12, 2020, at https://www.msn.com/en-us/news/technology/engineers-found-guilty-of-stealing-micron-secrets-for-china/ar-BB15oeqQ; UMC, press release, "UMC to Appeal the Court Decision on the Micron Case," June 12, 2020, at https://www.umc.com/en/News/press_release/Content/corporate/20200612.

[150] Department of Commerce, "Addition of Fujian Jinhua Integrated Circuit Company, Ltd. (Jinhua) to the Entity List," press release, October 29, 2018 (effective October 30, 2018), https://www.commerce.gov/news/press-releases/2018/10/addition-fujian-jinhua-integrated-circuit-company-ltd-jinhua-entity-list.

[151] The Committee on Foreign Investment in the United States (CFIUS) is an interagency body composed of nine Cabinet members, two ex-officio members, and other members as appointed by the President, that assists the President in reviewing the national security aspects of foreign direct investment in the U.S. economy. 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 include 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 always 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. For more information on CFIUS, see CRS Report RL33388, *The Committee on Foreign Investment in the United States (CFIUS)*, by James K. Jackson.

[152] For more information, see CRS Report R41916, *The U.S. Export Control System and the Export Control Reform Initiative*, by Ian F. Fergusson and Paul K. Kerr; CRS In Focus IF10952, *CFIUS Reform Under FIRRMA*, by James K. Jackson and Cathleen D. Cimino-Isaacs; and CRS Report RL33388, *The Committee on Foreign Investment in the United States (CFIUS)*, by James K. Jackson.

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

[154] 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*

2016, the Obama Administration blocked an affiliate of CICIIF from acquiring Aixtron, a leading producer of advanced semiconductor manufacturing equipment and processes.[155] In 2017, the Trump Administration blocked the acquisition of Lattice Semiconductor, a leader in the design of field-programmable gate array (FPGA) chips,[156] by a Chinese government-backed private equity fund based on a recommendation from CFIUS that found the transaction posed a national security risk.[157] The proposed sale of Xcerra, a semiconductor testing company, to a Chinese state-backed semiconductor investment fund was withdrawn due to the anticipation of a CFIUS recommendation to the President to block the deal.[158]

Table 5. Examples of Abandoned or Blocked Chinese Semiconductor Transactions

Year	Buyer	Target	Transaction Value	Status
2015	Tsinghua Unigroup	Micron Technologies	$23 billion	Abandoned
2016	China Resources Holdings	Fairchild Semiconductor	$2.6 billion	Abandoned
2016	Tsinghua Holdings	Western Digital Corporation	$3.78 billion	Abandoned
2016	Fujian Grand Chip Investment Fund	Aixtron	$723 million	Blocked
2017	Canyon Bridge	Lattice Semiconductor	$1.3 billion	Blocked
2018	Hubei Xinyan	Xcerra	$580 million	Abandoned

Source: Compiled by CRS from public reporting.

Notes: Each of the buyers in this table is supported by CICIIF.

Licensing of Dual-Use Technologies

The United States uses export controls to prevent China from acquiring leading-edge technology that may be used for military as well as commercial purposes, including semiconductors. Export controls restrict and require licenses for the transfer of controlled technologies.[159] The Trump

Street Journal, February 23, 2016.

[155] Presidential Order, *Regarding the Proposed Acquisition of a Controlling Interest in Aixtron SE by Grand Chip Investment GMBH*, December 2, 2016, at https://obamawhitehouse.archives.gov/the-press-office/2016/12/02/presidential-order-regarding-proposed-acquisition-controlling-interest.

[156] FPGAs are designed to allow post-manufacture programming or reprogramming of a chip for customized applications. The benefits of FPGAs include greater flexibility, ability to more quickly meet market needs, faster and parallel processing of signals, re-programmability, and ability for remote programming.

[157] U.S. Department of Treasury, "Statement on the President's Decision Regarding Lattice Semiconductor Corporation," press release, September 17, 2017, at https://www.treasury.gov/press-center/press-releases/Pages/sm0157.aspx.

[158] Securities and Exchange Commission, EDGAR System, Xcerra Corporation, 8-K filing, February 22, 2018, at https://www.sec.gov/Archives/edgar/data/357020/000119312518054209/d533034d8k.htm.

[159] The United States has imposed controls on exports from China related to semiconductors and semiconductor manufacturing equipment in various forms since the Cold War. The U.S. Department of Commerce's BIS and the Department of State's Directorate of Defense Trade Controls (DDTC) are the two primary agencies that administer export controls. They focus on dual-use technologies, including semiconductor goods, which can potentially have both commercial and military applications. In addition, DOD's Defense Technology Security Administration (DTSA) coordinates the technical and national security review of direct commercial sales export licenses and commodity justification requests, including reviewing and commenting on proposed and final rule changes on export controls from the Departments of Commerce and State. Also see CRS Report R41916, *The U.S. Export Control System and the Export Control Reform Initiative*, by Ian F. Fergusson and Paul K. Kerr, and CRS In Focus IF11627, *U.S. Export Control Reforms and China: Issues for Congress*, by Ian F. Fergusson and Karen M. Sutter.

Administration has strengthened U.S. export controls to address growing concerns about the potential national security ramifications of China's industrial and military policies in advanced and emerging technologies, including semiconductor-related technology. In 2018, Congress passed the Export Control Reform Act (ECRA, P.L. 115-232) in part to tighten dual-use technology exports to China and in response to China's military-civil fusion program, which is blurring distinctions between military and civilian end-use and end-users in trade.[160] As part of the efforts to tighten strategic trade with military-tied entities in China, in September 2020 the U.S. Department of Defense proposed adding SMIC to the Commerce Department Bureau of Industry and Security (BIS) Entity List due to its work with the Chinese military.[161]

The Trump Administration has also sought to curtail technology exports to Chinese companies of concern, such as Huawei. Since May 2020, BIS has amended rules to restrict Huawei Technologies Co. and its affiliates' ability to acquire chips from any source using U.S. design software or enabling equipment.[162] These restrictions affected TSMC's sales to China's Huawei; Huawei accounts for about 14% of TSMC's revenue. There has been growing public attention and consideration among U.S. policymakers about the role of U.S. semiconductor fabrication machines and tools in building China's domestic production capacity. (For more information on U.S. semiconductor machinery exports to China, see **Figure 7**.) BIS has specifically identified semiconductor fabrication equipment and semiconductors as subjects of further interest for future controls. While some industry analysts assert that U.S. restrictions could reinforce the Chinese government's commitment to develop "semiconductor independence," others note that China's efforts are already deeply rooted.[163]

China is seeking to fill technology gaps and using new pathways as acquisitions and technology transfer come under greater U.S. and foreign government scrutiny. For example, China's policies encourage the return of Chinese expatriates, the hiring of specialized foreign industry talent, and cross-border exchanges of personnel. Many of China's top technology firms have U.S. R&D centers in Silicon Valley and Seattle that partner with universities and hire local technology talent.[164] China also is stepping up its participation in U.S.-led open source technology platforms, such as RISC-V, as an alternative way to access U.S. semiconductor expertise.[165] These platforms

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[160] "Bureaucracy and Counterstrategy: Meeting the China Challenge," remarks by Christopher Ashley Ford, Assistant Secretary, Bureau of International Security and Nonproliferation, U.S. Department of State, September 11, 2019.

[161] The Entity List identifies persons involved, or with the potential to be involved, in activities contrary to U.S. national security or foreign policy interests. BIS typically requires a license for U.S. shipments of Export Administration Regulations (EAR) items to those on the Entity List. BIS presumes denial for some parties, but still can approve licenses on a case-by-case basis.

[162] BIS, "Commerce Addresses Huawei's Efforts to Undermine Entity List, Restricts Products Designed and Produced with U.S. Technologies," press release, May 15, 2020, at https://www.commerce.gov/news/press-releases/2020/05/commerce-addresses-huaweis-efforts-undermine-entity-list-restricts; and BIS, interim final rule and request for comments, "Export Administration Regulations: Amendments to General Prohibition Three (Foreign-Produced Direct Product Rule) and the Entity List," 85 *Federal Register* 29849, May 19, 2020, at https://www.federalregister.gov/documents/2020/05/19/2020-10856/export-administration-regulations-amendments-to-general-prohibition-three-foreign-produced-direct.

[163] James Andrew Lewis, "Managing Semiconductor Exports to China," Commentary, Center for Strategic and International Studies, May 5, 2020; Saif M. Khan, "Maintaining the AI Chip Advantage of the United States and its Allies," CSET Issue Brief, Center for Security and Emerging Technology (CSET), December 2019; and Saif M. Khan, "U.S. Semiconductor Exports to China: Current Policies and Trends," CSET Issue Brief, October 2020.

[164] Thilo Hanneman, Daniel H. Rosen, Cassie Gao, and Adam Lysenko, "Two-Way Street: US-China Investment Trends-2020 Update," *Rhodium Group*, May 11, 2020; Michael Brown and Pavneet Singh, "China's Technology Transfer Strategy," *Defense Innovation Unit Experimental (DIUx)*, January 2018.

[165] Runhua Zhao, "Briefing: China Sets up Domestic Chip Alliance," *Xinhua News Agency*, November 9, 2018; "China Mobile Deepens O-RAN Research, Showcasing Significant Achievements at MWC2019," *PRNewswire*, February 26,

offer Chinese firms and government institutes access to top U.S. technology talent to train and troubleshoot on particular projects.[166] For example, in 2019, Pingtouge, the chip subsidiary of Chinese company Alibaba, released its first processors—Xuantie 910 and Hanguang 800—that relied on foreign technology and expertise shared through RISC-V to develop the chips.[167]

Europe

European-headquartered semiconductor firms accounted for about 10% (~$40 billion) of global semiconductor sales in 2019 (see **Figure 4**). Three firms based in the European Union—STMicroeletronics, Infineon Technologies, and NXP Semiconductors—ranked among the world's top 15 semiconductor firms by sales in 2019 (see **Appendix B**).[168]

European-headquartered semiconductor companies tend to specialize in niche markets, including the automotive industry, energy applications, and industrial automation; these firms do little production of computer- and consumer-related chips.[169] Some European companies are considered strong in chip architecture, mobile telecommunications and industrial applications, and security chips (e.g., passports, IDs, and smartphones), a market dominated by NXP, Infineon, and STMicroelectronics.[170] Europe's share of global revenues for fabless firms is small (2%).

In May 2013, the European Commission (EC) announced an initiative aimed at increasing Europe's share of global semiconductor manufacturing by providing $11.3 billion (€10 billion) in public and private funding for R&D activities in an effort to induce about $113 billion (€100 billion) in industry investment in manufacturing.[171] The initiative called for a multipronged approach that included easing access to capital financing by qualified companies; pooling European Union (EU), national, and regional subsidies to enable larger-scale projects; and improving worker training.[172] The Commission's goal was for European firms to account for 20%

2019.

[166] The nature of open source allows participants in one country to gain from the technological expertise that resides in another country. Proponents of open source technology highlight its ability to speed technology development, ensure interoperability, and increase security by identifying and resolving problems more quickly. Critics highlight that open technology platforms explicitly threaten the core IP that has been developed by leading U.S. software and hardware companies. Others argue that open technology platforms are rapidly developing in a direction that could be used to exploit gray areas or gaps in U.S. export control authorities. See Caroline Meinhardt, "Open Source of Trouble: China's Efforts to Decouple from Foreign IT Technologies," *Mercator Institute for China Studies*, March 18, 2020.

[167] Josh Horwitz, "Alibaba's Chip Division Releases First Core Processor," *Reuters*, July 26, 2019, at https://www.reuters.com/article/us-alibaba-chip-design/alibabas-chip-division-releases-first-core-processor-ip-idUSKCN1UL0W6; Fangyu Cai, "Alibaba Open Sources Its MCU to Boost AI Research," *Synched*, October 10, 2019, at https://syncedreview.com/2019/10/23/alibaba-open-sources-its-mcu-to-boost-ai-research/; Arjun Kharpal, "Alibaba Unveils Its First AI Chip as China Pushes for Its Own Semiconductor Technology," CNBC, September 25, 2019, at https://www.cnbc.com/2019/09/25/alibaba-unveils-its-first-ai-chip-called-the-hanguang-800.html.

[168] In 2018, Qualcomm, NXP's rival, proposed a takeover of NXP, a move that it has since abandoned.

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

[170] "Semiconductors: European Chip Industry Aims to Get Back on the Map," *Handelsblatt*, April 30, 2018, at https://www.handelsblatt.com/today/companies/semiconductors-european-chip-industry-aims-to-get-back-on-the-map/23582014.html.

[171] European Commission, "Commission Proposes New European Industrial Strategy for Electronics—Better Targeted Support to Mobilize 100 Billion Euro in New Private Investments," press release, May 23, 2013, at https://ec.europa.eu/commission/presscorner/detail/en/IP_13_455.

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

of global chip manufacturing by 2020. The years-long program may have helped prevent Europe's market share in wafer fabrication from declining. European-based fabs accounted for 3% of global 300mm wafer fabrication production capacity in 2019, the same share as in 2015 (see **Table 1**).[173] Bosch and Infineon, among the most important suppliers of automotive semiconductors, are each constructing a new 300mm fab in Europe.[174]

The European Commission and European governments continue to seek ways to bolster Europe's microelectronics sector. A 2018 report, *Rebooting Electronics Value Chains in Europe*, prepared by Europe's semiconductor companies for the Commission, recommended that the EU provide additional funds for public-private partnerships in microelectronics manufacturing and other electronics components and systems.[175] France, Germany, Italy, and the United Kingdom[176] received Commission approval at the end of 2018 for a $2 billion (€1.7 billion) joint microelectronics project[177] aimed at encouraging investments in internet-connected devices and connected car technologies; this effort is scheduled for completion by 2024.[178] The Commission anticipates that this investment will stimulate roughly $6.7 billion (€6 billion) in private investment.

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 the semiconductor sector relative to foreign firms 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 successor technologies. A history of the federal role is provided in **Appendix A**; current research and development efforts are described below.

Europe," at https://ec.europa.eu/digital-single-market/en/electronics-strategy-europe.

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

174 Bosch, *Factsheet: 300 mm Wafer Fab in Dresden*, September 30, 2019, at https://www.bosch-presse.de/pressportal/de/en/300-mm-wafer-fab-in-dresden-200769.html, and Infineon Technologies AG, "Infineon Prepares for Long-Term Growth and Invests €1.6 Billion in New 300-Millimeter Chip Factory in Austria," press release, May 18, 2018, at https://www.infineon.com/cms/en/about-infineon/press/press-releases/2018/INFXX201805-054.html.

175 European Commission, *Boosting Electronics Value Chains in Europe*, A Report to Commissioner Gabriel, June 19, 2018, p. 12, at https://ec.europa.eu/digital-single-market/en/renewed-electronics-strategy-europe. Eleven companies and research bodies endorsed the report.

176 The United Kingdom's participation in the microelectronics project at the end of the Brexit transition period, likely to last until December 31, 2020, is unclear. See CRS Report R45944, *Brexit: Status and Outlook*, coordinated by Derek E. Mix.

177 The European Commission needs to be notified and approve state aid (a subsidy or any other aid) for projects by Member States, especially those that target a particular sector prior to its initiation.

178 Foo Yun Chee, "EU Okays $2 Billion Microelectronics Project by France, Germany, Italy, UK," *Reuters*, December 18, 2018. Also see European Commission, "State Aid: Commission Approves Plan by France, Germany, Italy, and the UK to give €1.75 Billion Public Support to Joint Research and Innovation Project in Microelectronics," press release, December 18, 2018.

Current Federal R&D Efforts to Develop Potential Technology Alternatives and Supplements to Semiconductors

Since the 1950s, semiconductors used for computer processing and memory storage have been based primarily on silicon. 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.[179] 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."[180] This has spurred other federal efforts to develop alternative approaches to computing to ensure the United States continues to enjoy the economic, competitiveness, and national security benefits of a robust domestic computing industry.

A number of technologies currently being explored may serve as complements or alternatives to today's silicon-based semiconductors. If successful, one or more of these technologies could have disruptive effects, positive or negative, on the semiconductor industry. Many of these emerging technologies rely on semiconductor hardware and continuing advances in semiconductor innovation. Among the technologies under development are quantum computing, optical computing, spintronic transistors, integrated photonics, and neuromorphic (brain-like) computing. Some of these technologies could, theoretically, offer vastly greater storage, processing, and transmission capabilities than current semiconductor technology.[181] China and other countries are also targeting these emerging technology fields.

The efforts underway face substantial technological obstacles to their realization. For example, physicists have been talking about the potential of quantum computing for more than 30 years, but the technology is still not ready for wide commercial use.[182]

National Strategic Computing Initiative. 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."[183] The executive order designated the DOE, the National Science Foundation (NSF), and DOD as the lead agencies, and designated the Intelligence Advanced Research Projects

[179] CMOS technology became the dominant technology for producing integrated circuits in the 1980s. Its low power consumption, low heat waste, and high noise immunity allow CMOS to integrate a high density of logic functions on a chip.

[180] 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, at http://www.nano.gov/sites/default/files/pub_resource/nni_fy17_budget_supplement.pdf.

[181] 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.

[182] Amit Katwala, "Quantum Computers Will Change the World (If They Work)," *Wired*, March 5, 2020, at https://www.wired.co.uk/article/quantum-computing-explained.

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

Activity (IARPA) and National Institute of Standards and Technology (NIST) as foundational R&D agencies.

The NSCI has continued during the Trump Administration. In June 2019, the White House Office of Science and Technology Policy established a Fast Track Action Committee on Strategic Computing under the National Science and Technology Council (NSTC) Subcommittee on Networking and Information Technology Research and Development (NITRD).[184] In November 2019, the NSTC released the report *National Strategic Computing Initiative Update: Pioneering the Future of Computing.* The report takes an expansive approach to computing that goes beyond semiconductor manufacturing, examining steps to realize:

> a computing ecosystem that combines heterogeneous computing systems (from extreme-scale to edge-centered systems and beyond) with the networking, hardware, software, data, and expertise required to support national security and defense as well as U.S. scientific, engineering, and economic leadership.[185]

With respect to computing hardware, the report's recommendations for federal actions include:

- providing long-term support for basic science and technology of computation to explore fundamental scientific and technical limits to computing to maximize the benefits of novel computational hardware, software, architectures, and new computing paradigms;
- providing support for the rapid translation to practice of basic R&D and technology;
- ensuring adequate investments in infrastructure such as foundries, testbeds, experimental systems, and prototypes, as well as in relevant domains such as materials science, microwave engineering, and supply chains; and
- aligning U.S. future computing initiatives with other major national initiatives.[186]

National Quantum Initiative. Quantum computing is one potential alternative to CMOS-based semiconductor technology. Quantum information science is believed to have the potential to provide computing capabilities for certain types of applications (e.g., code-breaking) that are far beyond what is possible with the most advanced technologies available today. Quantum science, generally, is the study of the smallest particles of matter and energy; quantum information science builds on quantum science principles to obtain and process information in ways that cannot be achieved based on classical physics principles.[187] The implications of the potential emergence of quantum computing on the semiconductor industry are unclear.

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[184] For additional information on the Office of Science and Technology Policy and the National Science and Technology Council, see CRS Report R43935, *Office of Science and Technology Policy (OSTP): History and Overview*, by John F. Sargent Jr. and Dana A. Shea.

[185] Executive Office of the President, National Science and Technology Council, Fast Track Action Committee on Strategic Computing, *National Strategic Computing Initiative Update: Pioneering the Future of Computing*, November 2019, p. iv, at https://www.nitrd.gov/pubs/National-Strategic-Computing-Initiative-Update-2019.pdf.

[186] Ibid., pp. 3-8.

[187] Whereas classical computing uses "bits" for data processing, quantum computing uses qubits. The practical difference between a bit and a qubit is that a bit can only exist in one of two states at a time, usually represented by a 1 and a 0, whereas a qubit can exist in both states at one time. This is a phenomenon called "superposition" and it is what allows the power of a quantum computer to grow exponentially with the addition of each bit. Two bits in a classical computer provides four possible combinations—00, 01, 11, and 10, but only one combination at a time. Two bits in a quantum computer provides for the same four possibilities, but, because of superposition, the qubits can represent all four states at the same time, making the quantum computer four times as powerful as the classical computer. So, adding

In 2018, Congress enacted the National Quantum Initiative Act (P.L. 115-368), which directed the President to establish a National Quantum Initiative Program to, among other things, "establish the goals, priorities, and metrics for a 10-year plan to accelerate development of quantum information science and technology applications in the United States." On August 30, 2019, President Trump established the National Quantum Initiative Advisory Committee (Presidential Executive Order 13885), in accordance with the act.[188] The advisory committee is composed of the Director of OSTP and up to 22 committee members from industry, universities, federal laboratories, and other federal government agencies appointed by the Secretary of Energy. The committee is to be co-chaired by the Director of OSTP and another committee member designated by the Secretary of Energy. In September 2018, the DOE and NSF announced awards of roughly $249 million to 188 research projects related to quantum information science. Government QIS basic research is also conducted by DOD, NIST, and the intelligence community.[189]

Electronics Resurgence Initiative (ERI). Launched by the Defense Advanced Research Projects Agency (DARPA) in 2017, ERI is a five-year, $1.5 billion DARPA program that seeks to address "long-foreseen obstacles to Moore's Law and the challenges impeding 50 years of rapid progress in electronics advancement."[190] In 2018, DARPA announced a new phase for the ERI that

> seeks to … push us toward a domestic semiconductor manufacturing sector that can implement specialized circuits; demonstrate that those circuits can be trusted through the supply chain and are built with security in mind; and are ultimately available to both [the Department of Defense] and commercial sector users.[191]

ERI Phase II research is focused on four key areas of development: 3D heterogeneous integration, new materials and devices, specialized functions, and design and security.

PowerAmerica. The Next Generation Power Electronics Manufacturing Innovation Institute is one of 14 institutes comprising a federal initiative known as Manufacturing USA, which seeks to bring government, industry, and academic partners together to "increase U.S. manufacturing competitiveness and promote a robust and sustainable national manufacturing R&D infrastructure."[192] PowerAmerica is co-funded by federal and nonfederal participants at $70 million each over five years. PowerAmerica R&D and related activities are focused on accelerating the development and large-scale adoption of wide-bandgap semiconductor technology in power electronic systems.

Joint University Microelectronics Program (JUMP). This public-private partnership, between DARPA and Semiconductor Research Corporation, which was launched in 2018, seeks to

a bit to a classical computer increases its power linearly, but adding a qubit to a quantum computer increases its power exponentially—doubling power with the addition of each qubit. CRS Report R45409, *Quantum Information Science: Applications, Global Research and Development, and Policy Considerations*, by Patricia Moloney Figliola.

[188] Executive Order 13885, "Establishing the National Quantum Initiative Advisory Committee," 84 *Federal Register* 46873, August 30, 2019.

[189] For more information on quantum information science, see CRS Report R45409, *Quantum Information Science: Applications, Global Research and Development, and Policy Considerations*, by Patricia Moloney Figliola.

[190] DARPA, "DARPA Announces Next Phase of Electronics Resurgence Initiative," press release, November 1, 2018, at https://www.darpa.mil/news-events/2018-11-01a.

[191] Ibid.

[192] Manufacturing.gov, "Highlighting Manufacturing USA," at https://www.manufacturing.gov/. PowerAmerica is one of six Manufacturing USA institutes funded by DOE. In addition, DOD has funded eight institutes and NIST has funded one. For more information on the Manufacturing USA institutes, see CRS Report R44371, *The National Network for Manufacturing Innovation*, by John F. Sargent Jr.

increase the performance, efficiency, and overall capabilities of commercial and military electronics applications.[193] Funding for JUMP, a five-year effort, is expected to exceed $150 million, with DARPA providing approximately 40% and consortium partners at six universities providing approximately 60%.[194] JUMP is a successor to the DARPA Semiconductor Technology Advanced Research Network (STARnet) program, which supported a collaborative network of research centers focused on "finding paths around the fundamental physical limits threatening the long-term growth of the microelectronics industry."[195]

Two of the JUMP centers focus on topics directly related to semiconductor design and manufacturing. The Applications and Systems-Driven Center for Energy-Efficient Integrated Nanotechnologies (ASCENT) studies material and device innovations to overcome the anticipated limits of current CMOS technology, while the Center for Research on Intelligent Storage and Processing-in-memory (CRISP) supports research to topple the "memory wall," a 70-year-old technical bottleneck in computer systems that is seen as hindering the use of big data for technical discovery.[196]

Nanoelectronics for 2020 and Beyond. This effort is organized under the National Nanotechnology Initiative (NNI)[197] "to discover and use novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures."[198] The effort's signature initiative and the NNI's Nanotechnology-Inspired Grand Challenge for Future Computing share a focus on next-generation computing technology R&D that would seek to overcome the anticipated limits of silicon-based semiconductor technology. The program is supporting DOD research on photonic approaches to quantum information processing as well as research at the National Institute for Standards and Technology on methods for improving production yields of electronic devices and to facilitate production processes for next-generation ultra-thin films.[199]

National Security Concerns

For decades, many have argued that maintaining a domestic manufacturing capability (or one in secure allied nations) for the most advanced semiconductor products is necessary for national security. The Department of Defense has expressed concerns about U.S. dependence on suppliers of semiconductors located outside the United States, especially suppliers in nations that are hostile or may become hostile to U.S. interests, a situation which may create vulnerabilities. In October 2020, Ellen M. Lord, Under Secretary of Defense for Acquisitions and Sustainment, testified:

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[193] The Semiconductor Research Corporation is a nonprofit research consortium founded in 1982 that supports semiconductor-related research and education programs with global operations.

[194] DOD, DARPA, "JUMP," at https://www.darpa.mil/about-us/timeline/jump.

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

[196] DOD, DARPA, "Joint University Microelectronics Program (JUMP)," at https://www.darpa.mil/program/joint-university-microelectronics-program.

[197] 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.

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

[199] NSTC, NSET, *The National Nanotechnology Initiative: Supplement to the President's FY2020 Budget*, p. 9, at https://www.nano.gov/sites/default/files/pub_resource/NNI-FY20-Budget-Supplement-Final.pdf.

> Reduced U.S. capability in microelectronics is a particularly troublesome area for the [Defense Industrial Base]. Government incentives and low labor costs in foreign countries have been the main drivers for the migration of microelectronics manufacturing, packaging, and testing to off-shore suppliers. This strains our ability to acquire and sustain microelectronic components embedded in systems critical to national security and national defense. Reliance on non-U.S. suppliers for microelectronics leaves DOD vulnerable. The risks of this reality include: availability of microelectronics in case of embargo; loss of U.S. intellectual property from offshore dependency; and loss of confidence the technology will function as intended due to possible malicious activity by foreign fabricators.[200]

Another risk of maintaining a domestic semiconductor production capability for critical military uses is that high costs could result in more expensive weapons systems and be financially unsustainable. Additionally, military systems may benefit from competition among semiconductor fabricators; in the absence of such competition, the technology for military systems may not advance as quickly.[201]

DOD Trusted Foundry Program

In October 2003, then-Deputy Secretary of Defense Paul Wolfowitz proposed a Defense Trusted Integrated Circuit Strategy. This strategy argued that the "country needs a defense industrial base that includes leading edge, trusted commercial suppliers for critical ICs used in sensitive defense weapons, intelligence, and communications systems."[202]

Faced with the globalization of semiconductor manufacturing, which DOD saw (and sees today) as diminishing its visibility into supply chains and production processes, DOD established the Trusted Foundry Program (later expanded to encompass other parts of the semiconductor supply chain in DOD's trusted supplier program) in 2004. Under this program, the government pays a fee to companies deemed secure sources to guarantee access to and the reliability of components important to national defense.[203] IBM began working with DOD in 2004 under a 10-year contract to serve as DOD's sole provider of leading-edge, secure foundry services. In 2014, however, IBM announced that GlobalFoundries, owned by Mubadala, an investment company controlled by the government of Abu Dhabi, would acquire the two IBM facilities covered under the Trusted Foundry Program contract. These facilities are located in Essex Junction, VT, and East Fishkill, NY.[204]

The Committee on Foreign Investment in the United States reviewed the transaction and in July 2015 cleared the acquisition.[205] GlobalFoundries then sought accreditation for the two facilities to

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[200] Testimony of Ellen M. Lord, Under Secretary of Defense for Acquisition and Sustainment, before the U.S. Congress, Senate Committee on Armed Services, Subcommittee on Readiness and Management Support, *Supply Chain Integrity*, 116th Cong., 2nd sess., October 1, 2020, https://www.armed-services.senate.gov/download/lord_-10-01-20.

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

[202] Department of Defense (DOD), *Defense Science Board Task Force on High Performance Microchip Supply*, December 2005, pp. 87-88, at https://dsb.cto.mil/reports/2000s/ADA435563.pdf.

[203] DOD's DMEA office administers and manages the trusted foundry and trusted supply programs. DOD Instruction 5200.44, *Protection of Mission Critical Functions to Achieve Trusted Systems and Networks*, details DMEA's rules specific to integrated circuits.

[204] Mubadala, "GlobalFoundries Completes Acquisition of IBM Microelectronics Business," press release, July 1, 2015, at https://www.mubadala.com/en/news/globalfoundries-completes-acquisition-ibm-microelectronics-business.

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

remain part of the Trusted Foundry Program. In April 2019, U.S.-headquartered ON Semiconductor announced it would purchase GlobalFoundries' East Fishkill facility for $430 million. GlobalFoundries plans to continue to operate the East Fishkill facility through 2022, when the facility is expected to come under ON Semiconductor's complete control.[206] DOD's current contract with GlobalFoundries to supply microchips provides one-year renewable options through 2023.[207]

In 2007, the Trusted Foundry Program was broadened to include design, assembly, testing, and packaging firms. DOD asserts that its trusted supplier accreditation plan has "expanded the ranks of suppliers capable of providing trusted services for leading-edge, state-of-the-practice and legacy parts by certifying that suppliers meet a comprehensive set of security and operations criteria." Trusted supplier accreditation is focused on security and requires secret clearance for facilities and personnel handling product or information and communications technologies connected to a product's manufacturing.[208] As of July 2, 2020, there were 78 accredited facilities.[209]

The Trusted Foundry Program faces several challenges. One is that the program is small, supplying only about 2% of the 1.9 billion semiconductors that DOD acquires per year.[210] According to DOD, "It was soon recognized that offering only IBM's capabilities left gaps in the trusted microelectronics supply chain. [The Trusted Foundry Program] was broadened to include other microelectronics suppliers to increase competition and ensure the entire supply chain could be trusted."[211] In addition, DOD recognizes that its needs represent only a small fraction (less than 1%) of global demand for semiconductors, making DOD a less financially attractive market than it once was. This presents two potential risks: a reduced ability to influence technology development and a loss of unique access to state-of-the-art technologies.[212]

In addition, DOD is concerned that GlobalFoundries, now one of a small number of secure foundries supplying the military, is falling behind other producers that can manufacture chips at

[206] GlobalFoundries, "ON Semiconductor and GLOBALFOUNDRIES Partner to Transfer Ownership of East Fishkill, NY 300mm Facility," April 22, 2019, at https://www.globalfoundries.com/news-events/press-releases/semiconductor-and-globalfoundries-partner-transfer-ownership-east; Gareth Halfacree, "GlobalFoundries Sells Fab 10 to On Semiconductor," bit-tech, April 23, 2019, at https://www.bit-tech.net/news/tech/cpus/globalfoundries-sells-fab-10-to-on-semiconductor/1/.

[207] DMEA awarded the current Trusted Foundry program contract, which expires on March 31, 2023, to GlobalFoundries under HQ0727-16-C-0001 on April 1, 2016. During the transition through the end of 2022, ON Semiconductor will essentially act as a customer for GlobalFoundries.

[208] Catherine Ortiz, outreach manager (contract), Defense Microelectronics Activity, DOD, "DMEA Trusted Foundry Program," PowerPoint presentation, pp. 23-34, October 10, 2017, at https://www.ndtahq.com/wp-content/uploads/2016/04/Ortiz-DMEA-Trusted-Foundry.pdf.

[209] Unlike GlobalFoundries, most accredited suppliers do not have contracts that guarantee a flow of defense-related orders. The Defense Microelectronics Activity (DMEA) maintains a list of suppliers on the DMEA Trusted IC Program website, at https://www.dmea.osd.mil/TrustedIC.aspx.

[210] Kirsten Baldwin, *Policy Perspective: The Current and Proposed Security Framework*, Department of Defense, August 16, 2016, p. 12, at https://www.ndia.org/-/media/sites/ndia/meetings-and-events/divisions/systems-engineering/past-events/trusted-micro/2016-august/baldwin-kristen.ashx?la=en.

[211] Catherine Ortiz, outreach manager (contract), Defense Microelectronics Activity, DOD, "DMEA Trusted Foundry Program," PowerPoint presentation, p. 23, October 10, 2017, at https://www.ndtahq.com/wp-content/uploads/2016/04/Ortiz-DMEA-Trusted-Foundry.pdf.

[212] 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, pp. 3 and 7; and Catherine Ortiz, outreach manager (contract), Defense Microelectronics Activity, DOD, "DMEA Trusted Foundry Program," PowerPoint presentation, October 10, 2017.

smaller feature sizes, potentially leaving the U.S. defense industry at a technological disadvantage.[213]

Beyond foundries, there is the broader issue of whether the global nature of the supply chain provides opportunities for foreign adversaries to hide malicious apps or software inside U.S. military systems. DOD perceives potential threats in other parts of the semiconductor production process, including design, fabrication, packaging, and testing. These concerns are being addressed, in part, through DOD's trusted supplier accreditation plan.[214]

For several years, DOD has implemented a new strategy for the Trusted Foundry Program, moving away from the sole-source trusted foundry approach and toward providing DOD access to commercially produced microelectronics by ensuring suppliers meet trusted and assured standards.[215] In 2019, Congress included Section 224 in the National Defense Authorization Act for Fiscal Year 2020 (P.L. 116-92), instructing DOD to establish supply chain and operational security standards for purchase of microelectronics products and services no later than January 1, 2021, and requiring that all microelectronic products purchased by DOD meet these standards by January 1, 2023.[216]

Among other efforts, in October 2019, the Undersecretary of Defense for Research and Engineering tasked the Defense Science Board to study the challenges in acquiring innovative and trusted microelectronics for the military, including how DOD can increase microelectronics production, assure access to trustworthy sources of supply, and explore how public-private partnerships may address any shortfalls. The microelectronics study is scheduled to be finished in 2021.[217] DOD also began an initiative in 2017, the Microelectronics Innovation for National Security and Economic Competitiveness (MINSEC) program. Its objectives include identifying ways to ensure that DOD can maintain its access to secure state-of-the-art design, fabrication, assembly, testing, and packaging capabilities. It also seeks to ensure that commercial domestic facilities can fabricate chips for DOD, and other end users, by meeting yet-to-be-developed industry-wide security standards and following other secure methods, including traceable and observable practices, for production of microelectronics across the supply chain.[218] In her October 2020 testimony, Under Secretary of Defense Lord stated:

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213 In 2018, GlobalFoundries announced it would provide services at 14nm and above nodes, but defense customers would need to find other suppliers for more advanced technologies at 10nm/7nm and beyond, choices that are currently limited to Intel, Samsung, and TSMC. In June 2020, GlobalFoundries and SkyWater announced that they would partner to make chips for U.S. defense programs.

214 Catherine Ortiz, outreach manager (contract), Defense Microelectronics Activity, DOD, "DMEA Trusted Foundry Program," PowerPoint presentation, October 10, 2017, p. 11.

215 Kristen Baldwin, *Long-Term Strategy for DOD Assured Microelectronics Needs and Innovation for National Economic Competitiveness*, DOD, October 24, 2018, p. 19, at https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2018/systems/Wed_21335_Baldwin.pdf.

216 The standards will systematize best practices relevant to manufacturing location, company ownership, workforce composition, access during manufacturing, suppliers' design sourcing, packaging, and distribution processes and reliability of the supply chain, and other matters germane to supply chain and operational security.

217 Memorandum from Mike Griffin, Undersecretary of Defense for Research and Engineering, to the Defense Science Board, October 30, 2019.

218 MINSEC has two other main objectives: to invest in niche capabilities for the military, such as radiation-hardened electronics and specialized RF and electo-optical chips and to develop a microelectronics-focused workforce in the United States. Also see Yasmin Tadjdeh, "Pentagon to Boost Investment in Microelectronics to Compete with China," *National Defense Magazine*, June 14, 2018, at https://www.nationaldefensemagazine.org/articles/2018/6/14/official-pentagon-investing-billions-into-microelectronics.

> [DOD is] proposing a new model to help restore U.S. microelectronics, which requires novel business concepts allowing DOD to leverage commercial market advancements and demand, which drive the microelectronics industry. Such novel relationships will allow government and industry to collaborate and co-invest to build and sustain domestic microelectronics capability that neither can afford to fund independently. Investment in industry's capability to produce high volume state-of-the-art microelectronics would provide the commercial sustainability that would then allow the production of low volume state-of-the-present and legacy parts DOD requires.[219]

Current Semiconductor-Related Legislation

The Trump Administration and Congress have sought to address concerns about U.S. semiconductor manufacturing competitiveness and the challenges posed by China through trade and investment measures.

In the past, congressional efforts related to semiconductors have largely focused on R&D. Two bills that Congress is currently considering would offer various incentives, including grants and tax credits, to induce investment in U.S.-based semiconductor manufacturing equipment and fabrication facilities, as well as authorizing funds for R&D activities.

The Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act (S. 3933/H.R. 7178) would, among other things: establish an investment tax credit for U.S.-based semiconductor manufacturing equipment and manufacturing facilities; authorize more than $15 billion for semiconductor R&D, workforce training, and related activities; authorize matching funds for state and local semiconductor programs; authorize funding to bolster DOD assured access efforts; and direct the Department of Commerce to assess the capabilities of the U.S. industrial base to support semiconductor design and manufacturing, and U.S. interdependencies with such capabilities in other countries.

The American Foundries Act of 2020 (S. 4130) would, among other things: authorize at least $25 billion for semiconductor-related R&D, construction of facilities, and acquisition of equipment and intellectual property; authorize incentives for the creation, expansion, or modernization of microelectronics manufacturing or advanced R&D facilities to meet the needs of the DOD and intelligence agencies for assured and secure microelectronics; and require the development of a plan to coordinate with foreign government partners on establishing common microelectronics export control and foreign direct investment screening measures to align with national and multilateral security priorities.

Additional details on the provisions in these acts are provided in **Appendix C**. The semiconductor industry's trade group, SIA, has endorsed both bills.[220] Others have raised questions about the high level of federal support for a single industry, arguing against establishing an industrial policy for semiconductors or any other industry.[221]

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[219] Testimony of Ellen M. Lord, Under Secretary of Defense for Acquisition and Sustainment, before the U.S. Congress, Senate Committee on Armed Services, Subcommittee on Readiness and Management Support, *Supply Chain Integrity*, 116th Cong., 2nd sess., October 1, 2020.

[220] SIA, "CHIPS for America Act Would Strengthen U.S. Semiconductor Manufacturing, Innovation," press release, June 10, 2020, at https://www.semiconductors.org/chips-for-america-act-would-strengthen-u-s-semiconductor-manufacturing-innovation/; and SIA, "American Foundries Act Would Provide Needed Investments in U.S. Semiconductor Manufacturing, Research," June 25, 2020, at https://www.semiconductors.org/american-foundries-act-would-provide-needed-investments-in-u-s-semiconductor-manufacturing-research/.

[221] See, for example, Thomas Duesterberg, "America Doesn't Need an Industrial Policy," *Wall Street Journal*, June 22,

A number of provisions in the Creating Helpful Incentives to Produce Semiconductors for America Act and the American Foundries Act of 2020 have been incorporated into the House and Senate versions of the FY2021 National Defense Authorization Act (NDAA).

The House version of the NDAA (H.R. 6395) would, among other things: authorize a semiconductor grant program to support construction, expansion, and modernization of semiconductor fabrication, assembly, testing, packaging, and advanced R&D facilities in the United States, providing up to $3 billion per grant; direct DOD to lead a multi-agency effort to incentivize the formation of a consortium of U.S. companies to ensure DOD and intelligence agencies have access to secure microelectronics; require an assessment of the capabilities of the U.S. industrial base to support semiconductor design and manufacturing, and U.S. interdependencies with such capabilities in other countries; establish and authorize funding for a Multilateral Semiconductor Security Fund to build safe and secure semiconductor supply chains; require the establishment of a Manufacturing USA institute focused on semiconductor manufacturing R&D; establish and authorize $914 million in FY2021 for a semiconductor technology center to conduct research and prototyping of advanced semiconductor technology; and authorize an additional $350 million for semiconductor-related R&D in FY2021. H.R. 6395 was passed by the House on July 21, 2020.

The Senate version of the FY2021 NDAA, the National Defense Authorization Act for Fiscal Year 2021 (S. 4049), includes provisions similar to those of H.R. 6395 described above, though it does not include the provision that would direct DOD to incentivize the creation of a consortium to ensure DOD and intelligence agencies have access to secure microelectronics. S. 4049 would also require DOD to certify that covered printed circuit boards are manufactured and assembled in the United States or certain nations for all future DOD contracts.

In addition, the Health, Economic Assistance, Liability Protection and Schools (HEALS) Act incorporates many of the provisions in S. 3933 and H.R. 7178.

Concluding Observations

Some policymakers assert that continued U.S. leadership in semiconductor technology, design, and fabrication is important to the U.S. economy and national security. In addition, others believe that these functions must not be interrupted by trade disputes or military conflict. In this regard, Congress may opt to consider how best to maintain continued U.S. semiconductor competitiveness, address ongoing discriminatory trade barriers and practices of concern, and ensure access to protected and secure sources of certain chips. The CHIPS for America Act and the American Foundries Act (AFA) of 2020 present approaches to addressing these concerns.

One key policy question is: What is the appropriate role for the federal government in seeking to ensure the U.S. position in semiconductors (or other industries)? For many years, Congress has debated the utility and fairness of policies that single out a technology, company, or industry for targeted government assistance. Advocates of such policies generally justify federal action based on the presumed benefits of attaining or retaining U.S. technology leadership, job creation, and economic growth, and furthering other policy objectives (e.g., fostering domestic manufacturing, furthering energy independence, or reducing carbon emission reductions). Opponents often characterize such policies as "industrial policy," "picking winners and losers," or "corporate welfare," arguing that the federal government should not attempt to supplant market forces and

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2020, at https://www.wsj.com/articles/america-doesnt-need-an-industrial-policy-11592845985; and Scott Lincicome, "Does the U.S. Semiconductor Industry Really Need Urgent Taxpayer Support to Stop China?," CATO Institute, July 23, 2020, https://www.cato.org/blog/does-us-semiconductor-industry-need-urgent-federal-support-stop-china.

decisions, and that such attempts are in any case unlikely to be effective; that government policies should be agnostic with respect to technology, company, and industry, not favoring one over another; that federal funding should not subsidize profitable companies; and that funding associated with such policies may be used to provide political rewards for favored constituents.

These criticisms have been of less concern in the context of the federal government's role in fostering technologies, products, and industries deemed central to U.S. national security. These defense-focused efforts have been less controversial, in part, because national defense is a constitutionally mandated function of the federal government and because, in the absence of government action, the technologies, products, and industries needed for national security would not exist.

The fact that semiconductor technologies and chip production are central to both economic and national security complicates the debate about the federal role in ensuring U.S. leadership and government access and assurance of chip fabrication and domestic availability. The Chinese government's announced plans to build independent capabilities in all parts of the semiconductor supply chain raise additional considerations for U.S. policymakers.

The programs and policies included in the CHIPS for America Act and the American Foundries Act of 2020 illustrate a variety of mechanisms through which the federal government could actively promote innovation by U.S.-based semiconductor companies and encourage domestic production. These mechanisms include:

- investments in R&D, including through the use of public-private partnerships;
- inducements, such as grants and tax benefits for establishing domestic production capacity for the fabrication of semiconductors, including semiconductor equipment and advanced assembly, testing, and packaging;
- support for investments in science, technology, engineering, and mathematics (STEM) education and skills training related to semiconductor design and fabrication;
- investments in the development of manufacturing machinery;
- investments in infrastructure (e.g., measurement technologies, standards, materials characterization) to support the semiconductor industry;
- efforts to coordinate and integrate federal activities; and
- efforts to assess the global semiconductor competitive environment and related federal policies.

The level of funding needed for each of these activities to accomplish its goals raises a set of relevant questions. For example: How large would the tax benefits need to be to induce semiconductor manufacturers to build future plants in the United States? How much would the federal government need to invest in R&D and related activities to ensure U.S. semiconductor technology leadership? How long would these incentives and investments need to be sustained? How much would the federal government need to invest in education and training to ensure an adequate workforce for expanded domestic semiconductor design, fabrication, and assembly, testing, and packaging? How much would it cost to ensure a domestic production source for some or all national security applications? Would Congress provide additional funding to cover the increased costs or would it require DOD to make trade-offs within its current budget?

Another set of questions relates to how other nations would respond to such efforts by the United States: Should federal policies to ensure continued U.S. access to semiconductors include a strategy that allows for reliance on allied nations as part of the semiconductor supply chain?

Should U.S. investments in semiconductor research or manufacturing be structured as part of a larger effort with allies and like-minded countries to incentivize R&D and supply chains and to counter China's state-led policies? What are the prospects to counter China's state-led policies through changes to global trade rules?

Congress may seek to assess the effectiveness of current U.S. authorities and global rules and approaches in addressing Chinese government direction, control, and subsidization of Chinese semiconductor activities and forcing foreign technology transfer. Such an assessment could evaluate whether new authorities and efforts are needed, including with regard to trade concerns such as state control of companies, subsidies, technology transfer, and other potential discriminatory practices.

Congress may want to evaluate U.S.-China technology ties that contribute to the development of China's indigenous semiconductor industry. These areas include China's investment in U.S. technology firms with niche and emerging capabilities; use of greenfield operations in the United States; imports of U.S. semiconductor equipment, tools, and software; licensing of U.S. technology; partnerships and joint ventures with U.S. firms; access to overseas foundries; hiring of foreign talent; and participation in open source technology platforms. Congress may also seek to address the full life-cycle of semiconductor capabilities developed with the support of U.S. government R&D investments in an effort to mitigate potential China-related risks. In particular, Congress might look for ways to further protect the integrity and use rights of commercial capabilities developed with the support of U.S. government investments. These issues may loom larger if, as some Members have proposed, there is a substantial increase in federal support for development of semiconductor technologies intended for exploitation by the private sector.

Congress may hold hearings and seek studies and analysis on these topics as it moves forward in its consideration of the legislation before it.

Appendix A. History of the Federal Role in Semiconductor Development and Competition

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 programmable 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 research investments during World War II, invented the transistor, a semiconductor device capable of regulating the flow of electricity.[222]

For the next decade, engineers sought to increase computer performance by overcoming the "tyranny of numbers," a term referring to the need to hand-solder the connections between a computer's many components. 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 to make all components the same size and shape, with built-in wiring, 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, 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.[223] 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, the government accounted for 100% of total U.S. IC sales; today, the government makes up less than 1% of the end-use market for microelectronics.[224]

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*

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

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

[224] David C. Mowery, "Federal Policy and the Development of Semiconductors, Computer Hardware, and Computer Software," Table 1, included as a chapter in the National Bureau of Economics Research publication *Accelerating Energy Innovation: Insights from Multiple Sectors*, May 2011, https://www.nber.org/chapters/c11753.pdf. See also Dave Chesebrough, "Trusted Microelectronics: A Critical Defense Need," *National Defense*, November 30, 2017, at https://www.nationaldefensemagazine.org/articles/2017/10/31/trusted-microelectronics-a-critical-defense-need.

remained at around 60%.[225] However, the rapid ascent of Japan's semiconductor industry in the early 1980s stirred concerns about a potential decline in the competitive position of the U.S. industry. By the late 1980s, the U.S. share of global semiconductor sales fell below 40%.[226]

When Japan captured the majority of the global DRAM market in the 1980s, the U.S. government alleged that Japanese companies achieved this position due to the Japanese government's protection of its domestic market, stifling the sales of U.S. semiconductors in Japan.[227]

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."[228]

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.[229]

The U.S. government responded to these 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).[230]

SEMATECH

In 1987, 14 U.S. semiconductor firms founded SEMATECH, a research consortium in Austin, TX. From FY1988 to FY1996, Congress provided a total of approximately $870 million to

[225] 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, at 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.

[226] 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*, Figure 6.1, 2012, at http://www.ncbi.nlm.nih.gov/books/NBK100307. Share data based on nationality of company.

[227] 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.

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

[229] Ibid.

[230] 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.

SEMATECH through the Defense Advanced Research Projects Agency (DARPA), generally matched by contributions from the industry participants.[231]

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."[232] A 1992 evaluation by the General Accounting Office, now the Government Accountability Office, 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.[233]

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."[234]

In July 1994, the SEMATECH Board of Directors voted to decline 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; it is now based in Albany, NY.

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[231] CRS Issue Brief 93024, *SEMATECH: Issues and Options*, June 12, 1996. Available to congressional clients from CRS upon request.

[232] 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, at http://www.nap.edu/download/12194.

[233] U.S. General Accounting Office (GAO, now known as the Government Accountability Office), *Federal Research: Lessons Learned from SEMATECH*, "Highlights," RCED-92-283, September 28, 1992, at http://www.gao.gov/products/RCED-92-283.

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

Appendix B. Top 15 Semiconductor Suppliers Worldwide

Table B-1. The Top 15 Semiconductor Suppliers Worldwide

Rank	Company	Headquarters Location	Operating Model	2019 Forecasted Sales (billions)	Main Business Segments
1	Intel	United States	IDM	$69.8	Microprocessors, logic, non-volatile memory, and FPGAs for computers, servers, and other electronic equipment
2	Samsung	South Korea	IDM	$55.6	Memory and logic
3	TSMC	Taiwan	Foundry	$34.5	Contract foundry
4	SK Hynix	South Korea	IDM	$22.9	Memory mainly
5	Micron	United States	IDM	$19.9	Memory and logic
6	Broadcom	United States	Fabless	$17.7	Integrated circuits
7	Qualcomm	United States	Fabless	$14.3	Chips for wireless modems and other phone-related devices mainly
8	Texas Instruments	United States	IDM	$13.5	Analog and logic devices for the automotive industry and other industrial applications
9	Kioxia (formerly Toshiba)	Japan	IDM	$11.3	Memory mainly
10	Nvidia	United States	Fabless	$10.5	GPUs and SoCs
11	Sony	Japan	IDM	$9.6	Integrated circuits
12	STMicro-electronics	Europe	IDM	$9.5	Analog and logic devices for the automotive industry and other industrial applications
13	Infineon	Europe	IDM	$8.9	Analog and logic devices for the automotive industry and other industrial applications
14	NXP	Europe	IDM	$8.3	Analog and logic devices for the automotive industry and other industrial applications
15	MediaTek	Taiwan	Fabless	$7.9	SoCs for wireless devices

Source: List prepared by IC Insights based on 2019 sales forecast.

Notes: Integrated device manufacturers (IDMs) operate in-house facilities worldwide where they can conduct chip design and manufacturing, as well as assembly, testing, and packaging. Fabless firms engage solely in chip design and partner with contract foundries (fabs that do not make IC products of their own design, but instead produce ICs for other companies) to manufacture designs into physical chips. FPGA=Field Programmable Gate Array. GPU = Graphics Processing Unit. System-on-a-chip (SoC) is a chip that integrates an entire system on a single chip.

Appendix C. Semiconductor-Related Legislation in the 116th Congress

The following bills related to addressing the semiconductor challenges discussed in this report have been introduced in the 116th Congress.

The Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act

The Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act (S. 3933/H.R. 7178) was introduced by Senators John Cornyn, Mark Warner, James Risch, Marco Rubio, and Kyrsten Sinema in the Senate and by Representatives Michael McCaul and Doris Matsui in the House. As introduced, the act would:

- establish a refundable investment tax credit for qualified semiconductor manufacturing equipment or manufacturing facilities located in the United States;[235]
- establish a program at NIST to support R&D in measurement science, standards, material characterization, instrumentation, testing, and manufacturing capabilities, and authorize, for FY2021 through FY2025:
  - $10 million per year for research to support the virtualization and automation of maintenance of semiconductor machinery;
  - $10 million per year for new advanced assembly, testing, and packaging capabilities; and
  - $30 million per year for developing and deploying semiconductor manufacturing-related educational and skills training curricula;
- establish a program at DOC to match semiconductor manufacturing incentive programs at the state or local level using funds from duties imposed under Section 301 of the Trade Act of 1974 deposited in a dedicated trust fund;
- authorize the use of at least $50 million in annual DOD research, development, test, and evaluation (RDT&E) appropriations to fund RDT&E and workforce training as prioritized by the Secretary of Defense in consultation with the Secretary of Commerce and the Secretary of Labor;
- direct DOC to assess the capabilities of the U.S. industrial base to support the national defense in light of the global nature of the supply chain and significant interdependencies between the United States industrial base and the industrial base of foreign countries with respect to the manufacture and design of semiconductors, and report to Congress within 90 days of enactment of this act;
- authorize $750 million for the establishment of a Multilateral Microelectronics Security Fund to support the development and adoption of secure microelectronics and secure microelectronics supply chains;
- direct the President to establish a new National Science and Technology Council subcommittee on matters relating to U.S. leadership in semiconductor technology

[235] If implemented, the tax credit would start at 40% in 2021, which would be in place through 2024, then it would fall to 10% in each of the next two years and expire in 2027.

and innovation, and direct the subcommittee to produce a national strategy on semiconductor research every five years;

- authorize $3.0 billion for a national semiconductor technology center, to conduct research and prototyping of advanced semiconductors in partnership between the private sector and DOD, DOE, NSF, and NIST;
- authorize $2.0 billion for the DARPA Electronics Resurgence Initiative;
- authorize $3.0 billion for NSF for basic research on semiconductors;
- authorize $2.0 billion for DOE for basic research on semiconductors; and
- authorize $5.0 billion annually from FY2021 to FY2025 to:
    - establish and operate an Advanced Packaging National Manufacturing Institute within DOC to support U.S. leadership in advanced microelectronic packaging;
    - promote standards development;
    - foster public-private partnerships;
    - develop R&D programs to advance technology development relevant to such packaging;
    - establish an investment fund to support a startup domestic advanced microelectronic packaging ecosystem, accelerate technology transfer, ensure domestic supply chains; and
    - work with the Department of Labor to develop workforce training programs and apprenticeships in advanced microelectronic packaging capabilities.

American Foundries Act of 2020

The American Foundries Act of 2020 (S. 4130), introduced by Senators Tom Cotton and Charles Schumer and nine others on July 1, 2020, would:

- authorize the Secretary of Commerce, in consultation with the Secretary of Defense, acting through NIST, to make grants of up to $3.0 billion to certain states to assist in financing the construction, expansion, or modernization (including acquisition of equipment and intellectual property) of microelectronics fabrication, assembly, test, advanced packaging, or advanced research and development facilities; authorize $15.0 billion in appropriations for FY2021 for this purpose, with funds remaining available through the end of FY2031; direct the Comptroller General to submit biennial reports to Congress on these activities;
- authorize the Secretary of Defense and the Director of National Intelligence, in consultation with the Secretary of Commerce, to jointly enter into arrangements with private sector entities or consortia to provide incentives for the creation, expansion, or modernization of one or more commercially competitive and sustainable microelectronics manufacturing or advanced R&D facilities capable of producing measurably secure and specialized microelectronics for use by the Department of Defense, the intelligence community, critical infrastructure sectors of the U.S. economy, and other national security applications; authorize $5.0 billion in appropriations for FY2021 for this purpose, with funds remaining available through the end of FY2031; direct the Comptroller General to submit biennial reports to Congress on these activities;

- authorize $2.0 billion in FY2021 appropriations to expand DARPA's Electronics Resurgence Initiative, with funds remaining available through the end of FY2031;
- authorize $1.5 billion in FY2021 appropriations for NSF microelectronics research, with funds remaining available through the end of FY2031;
- authorize $1.25 billion in FY2021 appropriations for DOE microelectronics research, with funds remaining available through the end of FY2031;
- authorize $250 million in FY2021 appropriations for NIST microelectronics research, with funds remaining available through the end of FY2031;
- direct the President to establish a National Science and Technology standing subcommittee on microelectronics policy which is to produce an annual national microelectronics research and development plan to guide and coordinate funding for breakthroughs in next-generation microelectronics research and technology, strengthen the domestic microelectronics workforce, and encourage collaboration between government, industry, and academia;
- direct the President to establish a President's Council of Advisors on Science and Technology standing subcommittee on microelectronics policy;
- direct a multiagency effort to develop and submit to Congress a plan to coordinate with foreign government partners on establishing common microelectronics export control and foreign direct investment screening measures to align with national and multilateral security priorities;
- prohibit any funding authorized under the act from being provided to foreign entities under the foreign ownership, control, or influence of the Government of the People's Republic of China or the Chinese Communist Party, or other foreign adversary, or that are determined to have beneficial ownership from foreign individuals subject to the jurisdiction, direction, or influence of foreign adversaries; and
- require the Secretary of Defense to establish requirements, and a timeline for enforcement of such requirements, for domestic sourcing for microelectronics design and foundry services by programs, contractors, subcontractors, and other recipients of DOD funding, within one year from the enactment of the act, and to update the requirements and timeline annually and to submit the information in a report to Congress.

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