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Semiconductors and the Semiconductor Industry

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Semiconductors and the Semiconductor Industry

SUMMARY

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Semiconductors (also known as integrated circuits, microelectronic chips, or computer chips) are tiny electronic devices (based primarily on silicon or germanium) composed of billions of components that can process, store, sense, and move data or signals. There are a number of types of semiconductor chips—including logic, memory, analog, optoelectronics, sensors, and discretes—each performing different functions and requiring specialized design and manufacturing processes. From 2012 to 2022, global sales of semiconductor chips doubled to $602 billion, accelerated by increasing digitization and connectivity across nearly every industry.

Advancing semiconductor performance is vital for enabling fast-growing market demands such as machine learning, vehicle electrification, and high-performance computing, and supporting U.S. national security interests. The semiconductor industry employs a number of strategies to improve the performance and energy efficiency of different types of chips, including creating chips with denser circuits, new architectures, and new materials. For logic chips (e.g., central data processing for computing devices), the manufacturing industry has continuously shrunk the size of key electronic features over the past six decades, using denser circuits to increase computing power. Certain advanced memory chips (e.g., NAND flash for long-term storage of videos and music) use new architectures in which manufacturers compete to stack layers of memory cells on top of one another like floors in a building; the most advanced NAND flash chips have over 200 layers. Next-generation power management chips used in vehicle electrification increasingly use materials other than silicon, called compound semiconductors, such as silicon carbide. Another emerging strategy to improve semiconductor device performance is the use of advanced packaging techniques; for example, stacking chips on top of one another in the same package to improve chip-to-chip communications.

Manufacturers also face ongoing demand for more established products, such as mature generations of chips, the scarcity of which forced auto manufacturers to temporarily shut down some assembly lines in early 2022. Supply chain resiliency for the production of mature chip technologies is essential for economic and national security across many sectors, including critical infrastructure, communications, medical devices, and defense, as well as integration into sophisticated end systems.

The semiconductor supply chain is composed of chip design and fabrication (or manufacturing), as well as assembly, test, and packaging (ATP) stages to prepare chips for final integration in electronic devices. The semiconductor industry relies on a wide network of materials, chemicals, gases, and manufacturing equipment suppliers. U.S.-headquartered firms lead in chip design and manufacturing equipment, accounting for the highest global revenues in 2021 for chip design (46%), as well as in the production of semiconductor manufacturing equipment (42%) and design software/licensing (72%). A small share of global manufacturing capacities is physically located in the United States for wafer fabrication (11%) and ATP services (5%); the majority of fabrication and ATP facilities are located in China, Taiwan, South Korea, and Japan.

The CHIPS Act of 2022 (Division A of P.L. 117-167), signed into law on August 9, 2022, appropriated funding for the Department of Commerce to carry out the CHIPS for America provisions enacted in the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (2021 NDAA, P.L. 116-283). These provisions include $39 billion in financial incentives to expand domestic manufacturing capacities across the semiconductor supply chain, including for wafer fabrication, advanced packaging, and semiconductor equipment and materials suppliers. The act also appropriated $11 billion for research and development programs to advance domestic capabilities to produce next-generation semiconductors.

Between 2020 and 2022, U.S.- and foreign-headquartered firms announced over $200 billion in private investments to expand domestic manufacturing capacities for semiconductor fabrication, equipment, and materials across 16 states. The Department of Commerce faces choices about how to deploy federal incentives to promote economically viable and competitive semiconductor technologies. The Department of Commerce anticipates three-quarters of the funds for semiconductor manufacturing, around $28 billion, will be awarded for facilities fabricating leading-edge logic and memory chips and the remaining funds for producers of specialty and mature chip technologies, industry suppliers, and ATP facilities. Funding allocations for different types and generations of chips, as well as different parts of the semiconductor supply chain, could be a subject of congressional oversight to evaluate the effectiveness of federal awards in promoting technological leadership, economic security of critical manufacturing industries, and national security.

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Introduction

Congress enacted the Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America program through the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (2021 NDAA, P.L. 116-283). It authorized provisions for semiconductor manufacturing, research and development (R&D), workforce training and education, and collaboration and coordination with allied and other friendly countries. Subsequently, the CHIPS Act of 2022 (Division A of P.L. 117-167), signed into law by President Joe Biden on August 9, 2022, appropriated $52.7 billion to carry out these provisions for FY2022-FY2027. It includes $39 billion in financial incentives to expand domestic manufacturing capacities across the semiconductor supply chain, including for fabrication and advanced packaging, as well as suppliers of semiconductor equipment and materials. The act also appropriated $11 billion for R&D programs to promote U.S. leadership in producing next-generation semiconductor technologies.

The Department of Commerce faces choices about how to deploy federal incentives to promote economically viable and competitive semiconductor technologies. Funding allocations for different types and generations of chips, as well as different parts of the semiconductor supply chain, could be a subject of congressional oversight to evaluate the effectiveness of federal awards in promoting technological leadership, economic security of critical manufacturing industries, and national security. This report on the semiconductor industry discusses the various types of semiconductor chips, trends in semiconductor design and innovation, the global landscape of the supply chain, and the competitiveness of the U.S. semiconductor industry to help inform congressional evaluation of these choices.

Semiconductor Chips

Semiconductors and Their Importance

Semiconductors (also known simply as integrated circuits, microelectronic chips, or computer chips) are tiny electronic devices (based primarily on silicon or germanium) composed of billions of components that can process, store, sense, and move data or signals—essentially serving as the brains, memory, sensors, communications, and power lines of electronic devices. There are a number of types of chips—including logic, memory, analog, optoelectronics, sensors, and discretes—each performing different functions and requiring specialized design and manufacturing processes.

Semiconductors are a uniquely important enabling technology. Fundamental to nearly all modern industrial and national security activities, semiconductors are also 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, along with concurrent cost reductions, has boosted U.S. economic output and productivity and enabled new products, services, and industries.

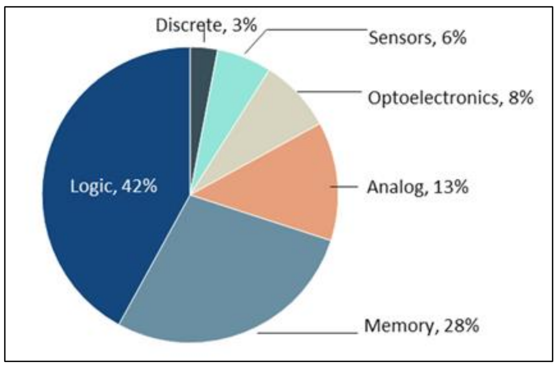
The semiconductor industry—and the industrial activities and systems it enables—forms the foundation of U.S. technological and industrial competitiveness and national security. Many policymakers see U.S. strength in the domestic production of semiconductors and the retention of manufacturing knowledge, human expertise, and hands-on experience as vital to U.S. economic and national security interests.

Semiconductor Chip Types

The semiconductor industry produces a wide variety of chips designed for precise functions, including processing, storing, sensing, and transmitting data, as well as power management. Multiple chips are typically integrated together on circuit boards to enable the operation of electronic devices such as smartphones, computers, and servers. Different types of chips are typically produced in separate facilities, and often by specialized firms, using unique manufacturing processes. From 2012 to 2022, global sales of semiconductor chips doubled to $602 billion to support increasing digitization and connectivity across nearly every industry.[1] Recent revenues have been composed mainly of sales of logic, memory, and analog chips (see **Figure 1**).[2] The remaining sales were for optoelectronics, sensors, and discrete semiconductors. The largest application markets for semiconductor demand globally in 2022 included communications (30%), computers (26%), automotive (14%), consumer electronics (14%), industrial (14%), and government (2%) end uses.[3]

Figure 1. Semiconductor Sales, 2021

Total: $556 billion



Source: CRS, adapted from Semiconductor Industry Association, *2022 Factbook*, May 2022, p. 12.

Logic Chips

Logic chips typically function as the "brains" of computing devices using a binary language (0's and 1's) to process information. Logic chips include microprocessors, such as central processing units (CPUs) for general-purpose computing and graphics processing units (GPUs) for video rendering. The logic chip category also includes relatively less expensive microcontrollers, which are designed to perform a particular task in applications such as power windows and seats in cars. The use of custom-designed logic chips for special functions like analytics and machine intelligence—also called accelerators—is also expanding to achieve better performance and energy efficiency.[4] For example, Google and NVIDIA have designed logic chips optimized for

[1] Gartner, "Gartner Says Worldwide Semiconductor Revenue Grew 1.1% in 2022," press release, January 17, 2023, at https://www.gartner.com/en/newsroom/press-releases/2023-01-17-gartner-says-worldwide-semiconductor-revenue-grew-one-percent-in-2022; Gartner, *Semiconductor industry revenue worldwide from 2012 to 2023*, November 2022, at https://www.statista.com/statistics/272872/global-semiconductor-industry-revenue-forecast/.

[2] Semiconductor Industry Association, *2022 Databook*, p. 15.

[3] Semiconductor Industry Association, *Chip Sales Rise in 2022, Especially to Auto, Industrial, Consumer Markets*, March 27, 2023, at https://www.semiconductors.org/chip-sales-rise-in-2022-especially-to-auto-industrial-consumer-markets/.

[4] IEEE, *Heterogeneous Integration Roadmap*, High Performance Computing and Data Centers, 2021, p. 10, at

supercomputing and artificial intelligence (AI) applications (sometimes referred to as "AI chips") that substantially reduce energy consumption, an important issue for AI and high-performance computing applications, compared with general-purpose chips.[5] The largest applications markets for logic chips include smartphones, high-performance computing (i.e., supercomputers and servers), Internet of Things devices (i.e., "smart" devices such as watches, speakers, and surveillance cameras), and the automotive sector (i.e., advanced infotainment systems and driver assistance systems).

U.S. Position and Competition in the Global Logic Chip Market

Logic chips accounted for the largest share of total global semiconductor sales in 2021, at about 42% ($232 billion).[6] In 2020, about 13% of global logic chip manufacturing capacity was physically located in the United States, and the majority was located in Taiwan (35%) and China (23%).[7] Most of the logic chip manufacturing facilities (also referred to as fabrication facilities or "fabs") owned by firms headquartered in the United States are operated throughout the world by integrated device manufacturers (IDMs) such as Intel.[8] More than 80% of the global capacity for producing logic chips is owned by contract manufacturers called foundries.[9] For the logic chip foundry segment, U.S. capacity (i.e., foundry capacity physically located in the United States) accounted for 7% of global foundry capacity in 2020. This capacity is primarily provided through facilities owned by Global Foundries and Samsung Foundries, with additional foundry capacity expected to come online by 2025 from Intel and TSMC.[10] In 2022, TSMC owned about half of the global logic chip foundry capacity.[11]

As of February 2023, two companies, TSMC and Samsung Foundries, had foundries capable of manufacturing the most advanced generations of logic chip technologies. These include chips labeled by the industry as 5 nanometer (nm) and 3 nm. These labels are not indicative of the chip's size or a physical aspect of the chip. Rather, the labels reflect different generations or technology nodes, with lower numbers representing more advanced manufacturing capabilities. Some market analysts project that Intel will begin manufacturing 7 nm chips in 2023 and 5 nm

https://eps.ieee.org/images/files/HIR_2021/ch02_hpc.pdf.

[5] Google and NVIDIA both rely on contract manufacturing for the production of their designs. David Patterson et al., "The Carbon Footprint of Machine Learning Training Will Plateau, Then Shrink," *Computer*, vol. 55, no. 7 (July 2022), p. 19.

[6] Semiconductor Industry Association, *2022 Factbook*, May 2022, p. 12, at https://www.semiconductors.org/wp-content/uploads/2022/05/SIA-2022-Factbook_May-2022.pdf.

[7] SEMI, *World Fab Forecast*, November 2020.

[8] An IDM is a semiconductor company that designs, manufactures, and sells integrated circuit (IC) products. In contrast, a contract fab, or foundry, manufacturers chips of other companies' design. Some companies, such as Samsung, both manufacture their own designs and offer foundry services for other companies. Companies that only design chips and outsource manufacturing are sometimes referred to as "fabless" companies.

[9] Center for Security and Emerging Technology, *The Semiconductor Supply Chain: Assessing National Competitiveness*, January 2021, p. 22, at https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf.

[10] Intel established Intel Foundry Services in 2021, stating that it was ushering in the "systems foundry era." "Instead of just supplying wafers to customers, which is the traditional foundry model, [Intel CEO Pat] Gelsinger said Intel offers silicon, packaging, software and chiplets." Intel, "Intel's Role as a Systems Foundry, Explained," October 17, 2022, at https://www.intel.com/content/www/us/en/newsroom/news/intels-role-systems-foundry-explained.html#gs.p32lsy.

[11] TSMC became the world's first pure-play foundry in 1987. A pure-play foundry only manufactures designs for others and produces no products of its own design. TrendForce, "Localization of Chip Manufacturing Rising. Taiwan to Control 48% of Global Foundry Capacity in 2022, Says TrendForce," press release, April 25, 2022, at https://www.trendforce.com/presscenter/news/20220425-11204.html.

chips in 2024 (or possibly 2023).[12] Orders for 3 nm chips reportedly are for logic chips designed for cryptocurrency mining, mobile phones, and high-performance computing, among other applications.[13] As node sizes have decreased (indicating increased complexity), the cost of designing logic chips has increased substantially. For example, it cost approximately $51 million for a single firm to design and prototype 28 nm chips in 2011 and approximately $542 million to design and prototype 5 nm chips in 2020.[14] The United States has historically been the global leader in logic chip design, with U.S.-headquartered firms accounting for 64% of revenues from logic chip sales in 2021.[15] However, many of these design firms (e.g., AMD, NVIDIA, Qualcomm, Broadcomm) do not have their own fabrication facilities (they are referred to as "fabless") and outsource the production of their designs to foreign-owned foundries located outside the United States. Only a few other logic chip manufacturers are capable of producing leading-edge chips, and those are a generation or two behind the 3 nm/5 nm nodes (e.g., U.S.-based Intel and a China-based foundry, Semiconductor Manufacturing International Corporation [SMIC]). With export restrictions in place on equipment and software to produce advanced nodes, SMIC may face challenges in mass producing 7 nm chips at high quality or producing more advanced nodes.[16]

Memory Chips

Memory chips store data. The majority of sales for memory chips are for two types of products: dynamic random access memory (DRAM) and NAND flash.[17] DRAM typically holds short-term data while a device is powered on, such as code needed by a computer processor to run programs; NAND flash provides long-term storage, such as preserving photos and music, even after a device is powered off. Over the past decade, the methods used to improve the performance of NAND flash memory chips have changed. The previous primary strategy to improve semiconductor chip performance was to shrink two-dimensional (2D) planar devices horizontally. The current strategy takes a three-dimensional (3D) approach by stacking layers of memory cells on top of one another, like the floors of a skyscraper. This method improves storage capacity and data reading/writing speeds without requiring more costly patterning equipment. Further, 3D NAND can use an older process node between 30 nm and 50 nm, reducing the cost and complexity of

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[12] See, for example, Jeremy Laird, "Next-gen Meteor Lake CPUs and Intel 4 node remain on track for 2023," *PC Gamer*, December 6, 2022, at https://www.pcgamer.com/next-gen-meteor-lake-cpus-and-intel-4-node-remain-on-track-for-2023.Areej; "Intel 3nm Process Node Coming Later this Year, Will Power 5th Gen Xeon Emerald Rapids-SP CPUs [Update]," *Hardware Times*, January 16, 2023, at https://www.hardwaretimes.com/intel-3nm-process-node-coming-later-this-year-will-power-5th-gen-xeon-emerald-rapids-sp-cpus/. For an explanation of nodes, see "Technology Nodes."

[13] Omar Sohail, "Samsung Officially Ships Its First Batch of 3nm GAA Chips, Beginning Its Run as the Only Company to Do So," *WCCF Tech*, July 25, 2022.

[14] Boston Consulting Group and Semiconductor Industry Association, *The Growing Challenge of Semiconductor Design Leadership*, November 2022, p. 13, at https://web-assets.bcg.com/3f/b4/fd384ccd46dc8a381bd61a648105/bcg-the-growing-challenge-of-semiconductor-design-leadership-nov-2022-r.pdf.

[15] Ibid., p. 5.

[16] TechInsights, *7nm SMIC MinerVa Bitcoin Miner*, July 2022, p. 3, at https://www.techinsights.com/blog/disruptive-technology-7nm-smic-minerva-bitcoin-miner; U.S. Department of Commerce, Bureau of Industry and Security, "Commerce Implements New Export Controls on Advanced Computing and Semiconductor," press release, October 7, 2022, at https://www.bis.doc.gov/index.php/documents/about-bis/newsroom/press-releases/3158-2022-10-07-bis-press-release-advanced-computing-and-semiconductor-manufacturing-controls-final/file.

[17] Craig Stice, *High Volume - Mainstream Memory*, Omdia, 2021, p. 2, at https://www.semiconductors.org/wp-content/uploads/2021/02/Highest-Volume-Mainstream-Memory_Omdia.pdf.

producing smaller features.[18] Memory chip makers have competed to increase the number of layers stacked in a device to bolster the storage capacity of smartphones and solid state drives, among other applications. The number of layers in 3D devices has increased from 24 layers in 2013 to more than 200 layers as of July 2022.[19] Memory chips are more commoditized than logic chips, using designs that are less application-specific than those used for logic chip production.[20] The largest applications markets for memory chips include mobile phones, data centers, and personal computing devices.[21]

U.S. Position and Competition in the Global Memory Chip Market

Memory chips accounted for about 28% of global semiconductor sales in 2021 ($154 billion).[22] Memory chip manufacturing has seen significant industry consolidation over the past three decades, in large part due to the tight profit margins in this segment (as is common for commoditized goods). Most memory chips are commoditized products for broad commercial use and benefit from economies of scale, creating pressures and incentives for consolidation.[23] For DRAM memory sales, Korean-headquartered Samsung and SK Hynix accounted for more than 70% of market share in 2021; U.S.-based Micron accounted for about 23%.[24] Recently, Micron announced it had started shipment on the most advanced DRAM process technology, called 1-alpha, with improved memory density and power savings compared with the previous three generations, which were derivatives of the 10 nm node memory chip.[25] For NAND flash memory sales, Korea-headquartered companies Samsung and SK Hynix and Japan-headquartered Kioxia accounted for about 53% of market share in 2021, and U.S.-headquartered Western Digital and Micron accounted for about 33% market share.[26] In 2020, Intel sold its flash memory business (less than 10% of the NAND market), including facilities in China, to SK Hynix.[27] Micron, Samsung, and SK Hynix are competing to mass produce 3D NAND chips with the highest

[18] Mark Lapedus, *3D NAND's Vertical Scaling Race*, SemiconductorEngineering, December 17, 2020, at https://semiengineering.com/3d-nands-vertical-scaling-race/.

[19] Micron, "Micron Ships World's First 232-Layer NAND, Extends Technology Leadership," press release, July 26, 2022, at https://investors.micron.com/news-releases/news-release-details/micron-ships-worlds-first-232-layer-nand-extends-technology.

[20] *Commoditized chips* refer to those that are mass produced and primarily differentiated by price rather than features such as power and performance.

[21] Yole Group, *Q1'22 DRAM and NAND Market Monitors*.

[22] Semiconductor Industry Association, *2022 Factbook*, May 2022, p. 12, at https://www.semiconductors.org/wp-content/uploads/2022/05/SIA-2022-Factbook_May-2022.pdf.

[23] McKinsey, *Memory: Are challenges ahead?*, November 2015, p. 30, at https://www.mckinsey.com/~/media/McKinsey/Industries/Semiconductors/Our%20Insights/McKinsey%20on%20Semiconductors%20Issue%205%20-%20Winter%202015/Memory%20are%20challenges%20ahead.ashx.

[24] Yole Group, *2021 DRAM Market Share, By Revenue*, at https://www.yolegroup.com/strategy-insights/spotlight-on-dram/.

[25] Micron, "Inside 1α—the World's Most Advanced DRAM Process Technology," press release, January 25, 2021, at https://media-www.micron.com/about/blog/2021/january/inside-1a-the-worlds-most-advanced-dram-process-technology.

[26] Trendforce, *NAND flash manufacturers revenue share worldwide from 2010 to 2022, by quarter*, May 2022, at https://www.statista.com/statistics/275886/market-share-held-by-leading-nand-flash-memory-manufacturers-worldwide/.

[27] NAND flash memory (named after the logic operation "NOT AND") provides long-storm storage even after a device is powered off to preserve data such as photos and music. Intel Corporation, "Intel Sells SSD Business and Dalian Facility to SK hynix," press release, December 29, 2021, at https://www.intel.com/content/www/us/en/newsroom/news/intel-sells-ssd-business-dalian-facility-sk-hynix.html#gs.fnr12q.

memory density by producing more than 200 layers per chip. China's industrial policies have sought to establish key leaders in the memory chip segment. Since its establishment in 2016, People's Republic of China (PRC) chipmaker Yangtze Memory Technologies Corporation (YMTC) has developed rapidly, reportedly having received $24 billion in subsidies from the PRC government. In November 2022, a reverse engineering firm claimed that YMTC had used a unique manufacturing approach to produce an advanced 3D NAND chip with 232 layers available in commercial products.[28] However, with export restrictions in place for NAND flash chips with 128 layers or more, and the addition of YMTC to the Entity List in December 2022, YMTC may face steep challenges in expanding manufacturing capacity because of limited access to U.S. equipment suppliers and services as well as to the U.S. market.[29]

Analog Chips

Analog chips provide a wide range of functions, including working with sensors to convert and modify analog signals (e.g., temperature, speed, and pressure, which can span a range of continuous values) into digital signals used by computers (i.e., discrete values made up of 0's and 1's).[30] Analog chip applications also include power management designed to convert, control, and distribute electrical power (e.g., AC to DC power conversion) in, for example, electric vehicles. Analog chips also are used for communications, including mobile phones (e.g., 5G, Bluetooth, wireless connectivity) and military detection and surveillance equipment (e.g., radar, sonar, infrared imaging). Globally, more than half of the analog chip market is for "application-specific" analog devices that are customized for specific end-users, designed by smaller teams, and produced in smaller batches compared with the typical high-volume production of commercial off-the-shelf logic and memory chips. The largest applications market for general-purpose analog chips in 2022 was power management, and the largest markets for application-specific analog chips include the communications, automotive, and industrial sectors.[31]

Next-generation power management and other chips are increasingly being fabricated on semiconducting materials other than silicon, called *wide band-gap* or *compound* semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN). Power management chips built on wide band-gap materials enable devices to operate at higher temperatures and voltages with increased efficiency and reliability.[32] The growing production of electric vehicles, along with the need for

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[28] TechInsights, *YMTC 232L TLC 3D NAND*, November 2022, at https://www.techinsights.com/sites/default/files/2022-11/TechInsights-DE-YMTC-232L-FINAL.pdf. For comparison of this NAND chip with Micron, Samsung, and SK Hynix, see TechInsights, "Comparison: Latest 3D NAND Products from YMTC, Samsung, SK hynix and Micron," press release, January 11, 2023, at https://www.techinsights.com/blog/comparison-latest-3d-nand-products-ymtc-samsung-sk-hynix-and-micron.

[29] The Entity List is maintained by the Bureau of Industry and Security, which requires (and issues) licenses to export items covered in the Export Administration Regulations to firms on the list. Bureau of Industry and Security, Department of Commerce, "Additions and Revisions to the Entity List," December 22, 2022; and Bureau of Industry and Security, "Commerce Implements New Export Controls on Advanced Computing and Semiconductor," press release, October 7, 2022, at https://www.bis.doc.gov/index.php/documents/about-bis/newsroom/press-releases/3158-2022-10-07-bis-press-release-advanced-computing-and-semiconductor-manufacturing-controls-final/file.

[30] In typical logic chips, transistors act as switches that turn on and off to represent the 0's and 1's used for processing information. In analog devices, transistors are not used as switches; instead, they operate across a range of electrical values to translate a wide range of incoming signals (e.g., temperature, pressure, speed). [30] IEEE, *International Roadmap for Devices and Systems*, Executive Summary, 2021, pp. 36-37, at https://irds.ieee.org/images/files/pdf/2021/2021IRDS_ES.pdf.

[31] IC Insights, *2022 Analog IC Sales Forecast*, March 25, 2022, at https://www.semimedia.cc/?p=12008.

[32] Semiconductors, under different conditions, can switch between being conductors of electricity and being insulators. Wide bandgap semiconductors such as SiC and GaN require more energy to switch between these states than silicon,

increasingly sophisticated systems to integrate renewable power generation into the electric grid, are likely to increase demand for wide band-gap semiconductors over the coming years. GaN semiconductors are used in fast-charging applications for consumer electronics, as well as in aerospace and defense applications, where they show improved reliability in high-radiation environments compared with silicon-based devices.[33]

U.S. Position and Competition in the Global Analog Chip Market

Analog chips accounted for about 13% of global semiconductor sales in 2021 ($74 billion).[34] The majority of top analog chip providers by revenue are IDMs that both design and manufacture their chips in-house. The design and manufacturing of analog chips have experienced less industry consolidation than the memory segment of the market. Analog chips typically require specialized designs for different end uses, producing relatively lower volumes of specialized products fabricated on mature generations of semiconductor. In this market segment, more mature nodes are not necessarily correlated with less sophisticated chips, highlighting how the potential complexity or sensitivity of semiconductor chip technology is not necessarily determined solely by node size. Since 2019, the semiconductor industry has invested more than $15 billion into the production of SiC semiconductors.[35] The leading suppliers of SiC wafers globally are U.S.-based Wolfspeed and Coherent Corporation (formally known as II-VI Incorporated). Most GaN wafers are produced in Taiwan.[36] In 2021, the three leading analog suppliers globally were U.S. firms: Texas Instruments, Analog Devices, and Skyworks Solutions. Collectively, these firms accounted for about 40% of the global market. Other analog suppliers include Europe-based Infineon and STMicroelectronics, as well as U.S.-based Qorvo, ON Semi, and Microchip.[37] Analog suppliers use a combination of in-house and foundry services to produce their products.

Optoelectronics, Sensors, Discretes (OSD)

Optoelectronic semiconductors are used to interact with or produce light. The largest applications markets for optoelectronics include light emitting diodes (LEDs); image sensors, such as those used in cameras; and laser diodes, such as those used in fiber optic communications. Other sensor applications include semiconductors (often integrating analog components) designed to detect or control properties such as temperature, pressure, and acceleration. Sensors have a wide array of applications in consumer electronics (e.g., mobile phones, vehicles, and industrial equipment). Discrete semiconductors typically perform a single electrical function—for example, controlling

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which can improve the efficiency in power electronics by reducing power losses. IEEE, *International Roadmap for Devices and Systems More than Moore White Paper*, 2021, p. 17, at https://irds.ieee.org/images/files/pdf/2021/2021IRDS_MtM.pdf. Department of Energy, *Semiconductor Supply Chain Report*, February 24, 2022, at https://www.energy.gov/sites/default/files/2022-02/Semiconductor%20Supply%20Chain%20Report%20-%20Final.pdf.

[33] EE Times, *The Next Silicon Frontier*, 2022, at https://www.eetimes.com/eetimes-50th-anniversary/.

[34] Semiconductor Industry Association, *2022 Factbook*, May 2022, p. 12, at https://www.semiconductors.org/wp-content/uploads/2022/05/SIA-2022-Factbook_May-2022.pdf.

[35] Yole Group, "A certain semiconductor in uncertain times," press release, December 20, 2022, at https://www.yolegroup.com/strategy-insights/a-certain-semiconductor-in-uncertain-times/.

[36] Department of Energy, *Semiconductor Supply Chain Report*, February 24, 2022, at https://www.energy.gov/sites/default/files/2022-02/Semiconductor%20Supply%20Chain%20Report%20-%20Final.pdf.

[37] IC Insights, *Leading analog integrated circuit (IC) suppliers worldwide from 2013 to 2021*, June 2022, at https://www.statista.com/statistics/555200/worldwide-analog-integrated-circuit-suppliers-by-revenue/#:~:text=In%202021%2C%20Texas%20Instruments%20earned,the%20sale%20of%20analog%20ICs.

electric current in an integrated circuit. These types of semiconductors are typically produced using mature node technology.

U.S. Position and Competition in the Global OSD Market

These types of semiconductors collectively accounted for about 17% of global semiconductor sales in 2021 ($96 billion). The market for these semiconductors is diverse, with many producers supporting a wide array of end applications. Producers include U.S.-based Diodes Inc., Vishay Intertechnology, Qorvo, dPix, and Cree. Other leading suppliers include Europe-headquartered companies ABB Ltd., Infineon Technologies, and STMicroelectronics, and Japan-headquartered Toshiba.[38] China's industrial policies support national optoelectronic semiconductor champions such as San'an.[39] China's efforts to acquire foreign semiconductor firms (such as the Chinese company Nexperia's attempted bid for U.K.-headquartered Newport Wafer Fab, a transaction recently blocked by the U.K. government) have sought to advance China's capabilities in compound semiconductors with potential power and defense applications.[40]

Where Different Types of Chips Are Manufactured

The majority of global chip manufacturing capacity in 2020 was owned by firms headquartered in the United States (22%), South Korea (20%), Taiwan (19%), China (15%), and Japan (12%).[41] For the most part, these firms locate their manufacturing facilities in the same set of countries, but the manufacturing share of different countries varies by chip type (see **Figure 2**).

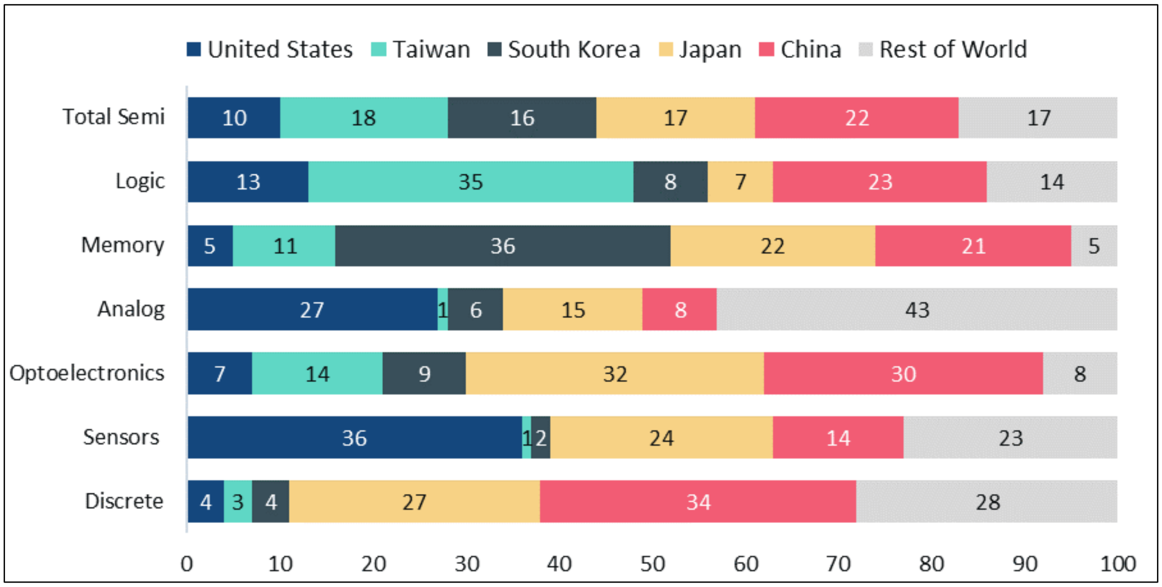
[38] The White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-based Growth*, June 2021, p. 30, at https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf.

[39] See the company's website at https://www.sanan-e.com/en/about.html.

[40] Although silicon is a semiconductor made from one element, compound semiconductors are made from two or more elements, such as silicon carbide or gallium nitride. For a discussion of Nexperia's history and its bid for Newport Wafer Fab, see CRS Report R46915, *China's Recent Trade Measures and Countermeasures: Issues for Congress*, by Karen M. Sutter.

[41] Center for Security and Emerging Technology, *The Semiconductor Supply Chain: Assessing National Competitiveness*, January 2021, p. 20, at https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf.

Figure 2. Wafer Manufacturing Capacity, by Fab Location and Chip Type, 2020



Source: CRS, adapted from SEMI, *World Fab Forecast*, November 2020.

Strategies to Improve Semiconductor Performance

The semiconductor industry has improved computational performance over the past six decades, primarily by steadily reducing the dimensions of key electronic features printed on the chip. Roughly every two years, the industry has doubled the number of transistors on a given logic chip area, delivering higher processing power at roughly the same cost. The pace of this innovation is often referred to as *Moore's law*, stemming from an empirical observation first made in 1965 by Gordon Moore, cofounder of Intel Corporation.

Due to fundamental limitations of reducing a chip's physical features, which are approaching the scale of a few atoms, and the high costs and technical difficulties of manufacturing at that scale, the pace of advancing computing performance using dimensional scaling (i.e., reducing transistors' dimensions on a chip)—the underlying expectation of Moore's law—has been slowing.[42] The cost to produce a 7 nm chip is four times that of a 45 nm chip, and the unit cost of a chip is expected to be higher at more advanced nodes (e.g., 5 nm and 3 nm).[43] Moreover, around 2005, ever-shrinking transistors led to unsustainable power consumption determined by fundamental device physics.[44] As a result, to improve computing performance, the semiconductor industry began to invest in strategies beyond dimensional scaling, including multicore processors,

[42] Boston Consulting Group and Semiconductor Industries Association, *Strengthening the Global Semiconductor Value Chain*, April 2021, p. 18, at https://www.semiconductors.org/wp-content/uploads/2021/05/BCG-x-SIA-Strengthening-the-Global-Semiconductor-Value-Chain-April-2021_1.pdf.

[43] IEEE Electronics Packaging Society, "Chiplet Definitions," at https://eps.ieee.org/technology/definitions.html.

[44] Leakage current, or current that leaks through the transistor even when it is in an off state, became an issue when the transistor was shrunk further around 2005, increasing the device power consumption unsustainably and limiting how much faster the computer could run without overheating.

specially designed chips (in contrast to generic, off-the-shelf chips), new materials and architectures, and advanced packaging techniques.[45]

Technology Nodes

Technology node, also referred to as process node, is an industry label that has been used to define and track successive generations of particular chip technologies over the past six decades. Node generally represents the size of key electronics on chips measured in metric length; the size of these features has now reached the scale of nanometers (nm), or one billionth of a meter. For logic chips, process node has historically been a measurement of transistor gate length (the gate is what controls the on/off state of the transistor to produce 0's and 1's for processing data). For DRAM memory chips, memory cells are the key electronic features; node sizes are still measured in nanometers but generally presented using "half-pitch," or half the distance between adjacent memory cells. Over time, the size of these features has been continuously reduced, enabling higher performance by allowing more components on the same chip. As shrinking the electronic features on chips became increasingly complex and costly for successive nodes, companies added new strategies to improve chip performance for certain products (e.g., 3D transistor and chip architectures such as 3D NAND chips, with layers of stacked memory cells, and new materials like compound semiconductors). Generally, the smaller the node size, the more advanced the semiconductor technology. However, for some type of chips, process or technology node may not be the most appropriate metric to capture advancements in performance. Moreover, mature node semiconductors may be critical components in sophisticated and advanced end systems such as power management and sensors.

A wide range of nodes is currently in production. For logic chips, these range from the most advanced 3 nm node, which began production in 2022, to mature generation nodes over 250 nm.[46] In 2021, 84% of global semiconductor production capacity was for nodes over 16 nm, according to one market research firm.[47] These mature generations of semiconductors are still in high demand, especially in fast-growing markets like 5G communications and smart devices. For example, out of the approximately 170 chips in a smartphone, fewer than 5% are for leading-edge nodes at 14 nm or below for the processor and memory, with the remainder of legacy chips providing functionalities for sensors, connectivity, and audio and power management.[48]

The CHIPS Act of 2022 requires that at least $2 billion of the $19 billion in FY2022 funding appropriated for semiconductor incentives be used for previous generations of semiconductor technologies, referred to in the act as "mature technology nodes." The Secretary of Commerce is to determine which technology nodes qualify as "mature" for funding purposes. Where to draw the line between advanced and mature nodes is subjective; there is no industry standard. Further,

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[45] CPUs originally contained one processor, also called a core, but increasingly have more than one processor, such as two in dual-core or four in quad-core CPUs. Performance improvements were also enabled by new materials (germanium, strained silicon, high-K/metal gate) and transistor structures (nonplanar transistors called FinFET) and placed into high-volume manufacturing by 2011. IEEE, *International Roadmap for Devices and Systems*, Executive Summary, 2021, pp. 10, at https://irds.ieee.org/images/files/pdf/2021/2021IRDS_ES.pdf.

[46] Samsung, "Samsung Begins Chip Production Using 3nm Process Technology With GAA Architecture," press release, June 30, 2022, at https://news.samsung.com/global/samsung-begins-chip-production-using-3nm-process-technology-with-gaa-architecture.

[47] Mario Morales, "Midway Through the Year: Are We at the Peak of this Current Semi Cycle?," presentation by IDC at Semicon West, San Francisco, CA, July 11, 2022.

[48] Based on a recent teardown analysis of 32 smartphones. Jean-Christophe Eloy, *Silicon and the Semiconductor Industry: What Lies Ahead*, Yole Group, The Next Silicon Frontier, 2022, p. 52, at https://www.eetimes.com/eetimes-50th-anniversary/.

because the semiconductor industry has seen rapid product development cycles, with new generations roughly every two years, any definition of mature or legacy chips may need to be revised over time. **Table 1** describes the classification of semiconductor facility types based on the generation of semiconductor technology from the first Department of Commerce Notice of Funding Opportunity (NOFO), released on February 28, 2023.

Table 1. Notice of Funding Opportunity for Expanding Domestic Chip Manufacturing Capacities

Semiconductor Facility Type	Eligible Facility Examples
Leading-edge	Facilities producing: • Advanced logic chips (described as below 5 nm or logic fabs using extreme ultraviolet patterning equipment) • Advanced memory chip (3D NAND chips with 200 layers or more and DRAM chips at half-pitch of 13 nm and below)
Current-generation	Facilities producing logic, analog, radio-frequency, and mixed-signal chips between 5 nm and 28 nm
Mature-node	Facilities producing: • Logic and analog (above 28 nm) • Discrete semiconductors • Optoelectronics • Sensors

Source: National Institute of Standards and Technology (NIST), U.S. Department of Commerce, *Notice of Funding Opportunity (NOFO), CHIPS Incentives Program–Commercial Fabrication Facilities*, February 28, 2023; NIST, U.S. Department of Commerce, *Funding Opportunity–Commercial Fabrication Facilities, Guide: Statement of Interest*, February 28, 2023, at https://www.nist.gov/system/files/documents/2023/02/28/CHIPS_NOFO-1_SOI_Instructions_Guide.pdf.

In September 2022, the Department of Commerce released a strategy document stating that about three-quarters of the $39 billion in funds appropriated for manufacturing incentives (about $28 billion) will be used for the production of leading-edge chips, while about $10 billion of the appropriated funds will go toward

- construction or expansion of facilities for the fabrication, packaging, assembly, and testing of mature- and current-generation chip technologies (including all types of logic, memory, discrete, analog, and optoelectronic chips);
- facilities to produce new or specialty technologies, such as advanced analog chips, radiation-hardened chips, compound semiconductors, and emerging technologies;
- facilities that manufacture equipment and materials for semiconductor manufacturing; and
- equipment upgrades that provide near-term efficiency improvements in fabs.[49]

The Commerce Department expects dozens of awards to be made for these purposes and, as with the investments in leading-edge semiconductors, anticipates that the advanced manufacturing

[49] U.S. Department of Commerce, *A Strategy for the CHIPS for America Fund*, September 6, 2022, p. 9, at https://www.nist.gov/system/files/documents/2022/09/13/CHIPS-for-America-Strategy%20%28Sept%206%2C%202022%29.pdf.

investment credit (AMIC) included in the CHIPS Act of 2022 will generate significant additional investment for participants.

Advanced Packaging

Advanced packaging includes many different innovative techniques to improve chip-to-chip communications and satisfy increasing demand for integrating more diverse functionalities into smaller device footprints. Over time, as transistor density has increased, traditional interconnects between chips have limited the speed at which memory, logic, and other chips can communicate. Many advanced packaging strategies have emerged to enable faster communications, including placing chips close to each other with a "bridge" (also referred to as a 2.5-dimensional, or 2.5D approach) or stacking them on top of one another (referred to as a three-dimensional [3D] strategy) to achieve the shortest distance between interconnections while decreasing the spatial footprint in the end device.[50]

This growing segment of the semiconductor supply chain can offer improved device performance for chip applications (and thus higher value), which may provide more economic feasibility for reshoring to the United States than traditional, low-value-added packaging operations.[51] Companies eligible to apply for funding incentives from the CHIPS Act of 2022 include domestic advanced packaging facilities. According to a market research firm, advanced packaging accounted for 40% of the packaging market share in 2020 and is expected to increase to 60% by 2030.[52] The United States accounted for nearly a quarter of global advanced packaging production capacity in 2020, led by Intel and Amkor. Taiwan leads in advanced packaging capacity, primarily due to capacity at firms ASE Group, TSMC, Chipbond, and ChipMOS.[53]

Chiplets

Another tool to promote semiconductor innovation is the use of "chiplets." Electronic devices such as smartphones and tablets require complex electronic functionalities in small footprints. To accommodate this requirement, the semiconductor industry shifted to integrating multiple elements of computing systems (e.g., CPU, GPU, USB controllers, network interfaces) on a single piece of silicon, often referred to as a system on a chip (SoC). Over time, as more functionalities were needed and it became costlier and more challenging to produce all features on the most advanced nodes, the industry has increasingly used separate building blocks called chiplets. In this process, functions previously performed by a single chip are divided into discrete functions and fabricated into smaller building blocks, so that only those blocks that need the

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50 IEEE, *Heterogeneous Integration Roadmap Single Chip and Multi-Chip Integration*, October 2019, pp. 10-14, at https://eps.ieee.org/images/files/HIR_2019/HIR1_ch08_smc.pdf.

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

52 GlobeNewswire, "Advanced Packaging Market Worth $55 Bn, Globally, by 2028 at 8% CAGR—Exclusive Report by The Insight Partners," press release, February 20, 2022, at https://www.globenewswire.com/en/news-release/2022/02/15/2385153/0/en/Advanced-Packaging-Market-Worth-55-Bn-Globally-by-2028-at-8-CAGR-Exclusive-Report-by-The-Insight-Partners.html#:~:text=The%20advanced%20packaging%20industry%20held,semiconductor%20packaging%20market%20by%202030.

53 Based on the top 10 companies, which comprised 93% of total advanced packaging capacity in 2020. Santosh Kumar, Stefan Chitoraga, and Favier Shoo, *Status of the Advanced Packaging Industry 2021*, Yole Development, September 2021, p. 66.

highest performance (e.g., the logic component) use the most advanced process nodes, while other blocks (e.g., input/output power) use mature process nodes.[54]

The chiplet fabrication process allows unique chiplets to be purchased from different vendors and packaged together using a "plug-and-play" approach to provide devices with enhanced functionality (that is, as long as they are designed to communicate with one another). An industry effort is under way to standardize chiplet design to improve the ability to mix-and-match in the market and to enable an "open chiplet ecosystem" for end-application developers to optimize hardware to their specific requirements.[55] Promoting the chiplet ecosystem can encourage innovation when traditional strategies for improving performance may be cost-prohibitive and create barriers to entry for new companies in the design and fabrication of specialized chips. China's semiconductor industry has become increasingly interested in chiplets as a way to work around current U.S. export controls and address certain capability gaps.[56]

The Global Nature of Semiconductor Production

The process of producing a finished semiconductor chip involves design and fabrication (i.e., manufacturing), as well as assembly, testing, and packaging (ATP). In many cases, these stages now occur across national borders among a small group of countries that specialize in particular parts of the supply chain. In some cases, a semiconductor chip can cross international borders 70 times during the production process.[57] U.S.-headquartered firms lead globally in chip design and manufacturing equipment, accounting for the highest global revenues in 2021 for chip design (46%), as well as the production of semiconductor manufacturing equipment (42%) and design software/licensing (72%). A small share of global manufacturing capacities is physically located in the United States for wafer fabrication (11%) and ATP services (5%); the majority of fabrication and ATP facilities are located in China, Taiwan, South Korea, and Japan.[58] In addition, the semiconductor supply chain relies on U.S. and other global suppliers of materials, chemicals, gases, and manufacturing equipment.

Semiconductor Industry Business Models

Up until the 1980s, a single company—known as an integrated device manufacturer (IDM)—typically operated most or all stages of chip production in-house. Although many types of chips (e.g., memory and analog chips) still operate primarily under the IDM model, advanced logic chips are now produced mostly by different companies that specialize in particular segments of

[54] IEEE Electronics Packaging Society, "Chiplet Definitions," at https://eps.ieee.org/technology/definitions.html.

[55] Several semiconductor and technology firms, including AMD, ARM, Intel, Meta, TSMC, Microsoft, Qualcomm, and Samsung, have formed an industry consortium to standardize how different chiplets connect to one another so that customers can mix the products of different companies. Universal Chiplet Interconnect Express, "Leaders in semiconductors, packaging, IP suppliers, foundries, and cloud service providers join forces to standardize chiplet ecosystem," press release, March 2, 2022, at https://www.uciexpress.org/_files/ugd/0c1418_e7fa0820a56042d192bfa4e7d3493742.pdf.

[56] Che Pan, "Tech War: Is the 'Chiplet' a Short Cut for China to Address its Semiconductor Self-sufficiency or a Wrong Turn?," *South China Morning Post*, May 26, 2022.

[57] Accenture and Global Semiconductor Alliance, *Globality and Complexity of the Semiconductor Ecosystem*, 2020, p. 6, at https://www.accenture.com/_acnmedia/PDF-119/Accenture-Globality-and-Complexity-Semiconductor-POV.pdf.

[58] Arizona Commerce Authority and Boston Consulting Group, *The National Semiconductor Economic Roadmap*, December 2022, p. 21, at https://web-assets.bcg.com/52/6b/7217e856495a83ac0b8447a2187e/national-semiconductor-economic-roadmap-nser-dec2022.pdf.

the supply chain. This specialization allows companies to manage the increasing costs of design and production associated with new technologies and to benefit from economies of scale. U.S.-based semiconductor firms first offshored relatively more labor-intensive and lower-value-added activities such as assembly, test, and packaging in the 1960s, followed by wafer fabrication in the 1980s with the advent of the "fabless/foundry" business model. Contracted facilities for assembly, test, and packaging services are known collectively as Outsourced Semiconductor Assembly and Testing (OSAT).[59]

A fabless company designs chips but does not have its own fabrication facilities; instead it contracts out the manufacture of its chips to foundries—companies that manufacture chips for other companies and that generally do not design and manufacture their own chips. As the costs and complexity of manufacturing advanced semiconductor chips increased over time, the number of IDMs operating fabs fell. Globally, at the 130 nm process node for nonmemory chips, there were 22 IDMs operating their own fabs; at the 22 nm mode, there were three IDMs, with the majority of chip designers becoming fabless and outsourcing manufacturing to foundries.[60] The advent of foundry services has enabled companies that typically relied on off-the-shelf semiconductor chips (e.g., Apple and Google) to join the semiconductor supply chain and design chips optimized for their particular applications. Four of the top 10 semiconductor vendors globally by revenue in 2022 were U.S.-headquartered fabless chip designers (Qualcomm, Broadcom, AMD, and Apple) that rely largely on foundry and contracted ATP services in Taiwan, South Korea, and China.[61]

Design

In the design process, companies conceive new products and specifications to meet customer needs and use these ideas to create particular logic and circuit designs for manufacture. In 2020, firms headquartered in the United States led globally in chip design, accounting for about 60% of global chip sales by companies that design only chips.[62] 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.[63]

To handle the design of complex circuits with billions of electronic features, chip designers typically use software called Electronic Design Automation (EDA). EDA providers usually license certain parts of the fundamental chip design so that designers do not need to recreate it, thereby saving time and money and allowing designers to focus on innovative changes. These proprietary designs are also referred to as intellectual property (IP) blocks. Chips used in personal computers contain dozens of IP blocks for various functions, such as wireless communications and ethernet connections. In 2021, firms headquartered in the United States accounted for the

[59] U.S. Government Accountability Office, *Offshoring U.S. Semiconductor and Software Industries Increasingly Produce in China and India*, GAO-06-423, September 2006, p. 10, https://www.gao.gov/assets/gao-06-423.pdf.

[60] Daniel Nenni and Paul McLellan, *Fabless: The Transformation of the Semiconductor Industry*, SemiWiki.com LLC, 2019, p. 110, at https://semiwiki.com/books/Fabless%202019%20Version%20PDF.pdf.

[61] For a list of the top 10 semiconductor companies by revenue in 2022, see Gartner, "Gartner Says Worldwide Semiconductor Revenue Grew 1.1% in 2022," press release, January 17, 2023, at https://www.gartner.com/en/newsroom/press-releases/2023-01-17-gartner-says-worldwide-semiconductor-revenue-grew-one-percent-in-2022.

[62] Semiconductor Industry Association, *2021 State of the U.S. Semiconductor Industry*, p. 16, at https://www.semiconductors.org/wp-content/uploads/2021/09/2021-SIA-State-of-the-Industry-Report.pdf.

[63] 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.

largest share of revenues from EDA and IP (72%), followed by Europe (20%).[64] The top EDA software providers include U.S.-headquartered Synopsys and Cadence, as well as Siemens EDA (U.S.-founded as Mentor Graphics and acquired by Germany-headquartered Siemens in 2017).[65] ARM Ltd., a company headquartered in the United Kingdom and owned by Japan's SoftBank, is the top provider of IP blocks for the semiconductor industry. The majority of global mobile phone processors are based on IP designs from ARM Ltd. An open-source technology platform called RISC-V, first developed at the University of California, Berkeley, in 2010, has been gaining traction in chip design, providing an accessible alternative to licensing proprietary designs from companies such as ARM Ltd.

Process Design Kits (PDKs) are used to translate semiconductor designs, made by EDA software, into manufacturable processes and are specific to the foundry and generation of technology (process node). Restrictive and expensive PDK licensing by foundries can inhibit small and medium-sized innovators from realizing the production of their designs. Some companies are partnering to offer open-source PDK to new designers, to promote innovation and enable them to produce chips more quickly.[66]

Fabrication

After the design stage, semiconductor chips are manufactured, or fabricated, in facilities often referred to as fabs or foundries. In this front-end fabrication process, chips are manufactured on circular sheets of silicon or, less commonly, other semiconducting materials, called wafers, that are typically about 8 or 12 inches in diameter. Each circular silicon wafer typically contains hundreds of different chips (usually tiny rectangles, smaller than the size of a postage stamp). To produce billions of electronic features on each chip (e.g., transistors), the wafer is covered in a light-reactive material and exposed to particular sources of light through a mask, similar to a stencil, containing the blueprints for the circuit pattern; this process is known as photolithography. After exposure, the unreacted materials and underlying silicon can be etched or removed to create complex circuit patterns on the wafer. Other manufacturing steps include adding materials (deposition and implantation), wafer cleaning and smoothing (wet cleaning and planarization), and thermal treatments (diffusion and annealing). The manufacturing sequence, which can require more than 1,000 process steps to make advanced logic chip designs, relies on specialized equipment and materials that are customized and calibrated according to a customer's design. In addition, manufacturers conduct a significant amount of research and development to determine the optimal conditions in which to process the wafer (e.g., optimized temperatures and chemical mixes) and to produce the highest number of functioning chips (also known as yield). These recipes and the equipment calibrations are proprietary.

Fabs source equipment and materials from a wide array of global suppliers. It takes more than four months, on average, to complete production of a chip order. In 2021, fabrication facilities located in the United States accounted for 11% of global semiconductor manufacturing capacity; the majority of capacity was located in China (21%), Taiwan (19%), South Korea (17%), and

[64] Arizona Commerce Authority and Boston Consulting Group, *The National Semiconductor Economic Roadmap*, December 2022, p. 21, at https://web-assets.bcg.com/52/6b/7217e856495a83ac0b8447a2187e/national-semiconductor-economic-roadmap-nser-dec2022.pdf.

[65] TrendForce, "New US EDA Software Ban May Affect China's Advanced IC Design, Says TrendForce," press release, August 15, 2022, at https://www.trendforce.com/presscenter/news/20220815-11338.html.

[66] For an example, see Google Open Source, "SkyWater and Google expand open source program to new 90nm technology," press release, July 28, 2022, at https://opensource.googleblog.com/2022/07/SkyWater-and-Google-expand-open-source-program-to-new-90nm-technology.html.

Japan (16%).[67] Fabs can operate as contract manufacturers and produce chips for a variety of different customers (foundries), produce their own in-house designs (IDMs), or do a combination of both. In 2021, contract foundries accounted for roughly one-third of global production capacity for chips, with most foundry capacity located in Taiwan, South Korea, and, to a lesser extent, China.[68]

Assembly, Test, and Packaging

After front-end fabrication of the chips, wafers are typically sent to other facilities for back-end manufacturing activities such as assembly, test, and packaging (collectively known as ATP). In these steps, chips are cut from the silicon wafer, tested for performance, and packaged to protect the chip and to allow for its integration into finished electronic devices by attaching electrical interconnections. Multiple chips with different functions, such as microprocessors, graphics processors, and memory, are individually packaged and mechanically assembled on a printed circuit board, connected by wires or pins.[69] Contract ATP manufacturers, similar to foundries used in fabrication, are often referred to as Outsourced Semiconductor Assembly and Test (OSAT) firms. In 2021, 5% of global ATP capacity was physically located in the United States; the majority of capacity was located in China (38%), Taiwan (19%), and South Korea (9%).[70] Technical advancements in packaging innovation can provide enhanced functionalities for chip applications, offering higher value and making reshoring to the United States more economically feasible than traditional, low-value-added packaging operations.[71]

Advanced Packaging

Materials, Chemicals, and Gases

Semiconductor manufacturing and packaging facilities require a diverse array of raw and processed materials, chemicals, and gases. Some examples include raw polysilicon and silicon wafers, chemicals such as hydrogen fluoride and nitric acid, and gases such as helium and neon. Many suppliers of these components also typically serve other industries with commodity chemicals and gases. Some specialty components are used primarily in the semiconductor industry and may present increased risk for supply chain disruptions. For example, the semiconductor industry accounts for nearly 90% of global demand for neon gas to produce the lasers needed during the photolithography process (i.e., printing circuit patterns onto silicon wafers). Ukraine supplies up to 90% of the neon gas used for semiconductor manufacturing in the

[67] Arizona Commerce Authority and Boston Consulting Group, *The National Semiconductor Economic Roadmap*, December 2022, p. 21, at https://web-assets.bcg.com/52/6b/7217e856495a83ac0b8447a2187e/national-semiconductor-economic-roadmap-nser-dec2022.pdf.

[68] Mario Morales, "Midway Through the Year: Are We At the Peak of this Current Semi Cycle?," presentation by IDC at Semicon West, San Francisco, CA, July 11, 2022.

[69] Known in the industry as *wire bonding*, whereby different semiconductor components/chips are connected using thin wires made of gold or aluminum due to simplicity and low cost.

[70] Arizona Commerce Authority and Boston Consulting Group, *The National Semiconductor Economic Roadmap*, December 2022, p. 21, at https://web-assets.bcg.com/52/6b/7217e856495a83ac0b8447a2187e/national-semiconductor-economic-roadmap-nser-dec2022.pdf.

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

United States and an estimated 50% of the global neon gas market. The 2014 and 2022 Russian invasions of Ukraine have led to neon gas shortages and high price increases.[72]

Nearly 90% of the semiconductor industry's silicon wafers are supplied by five firms, headquartered in Japan (SUMCO and Shin-Etsu, 49%), Taiwan (GlobalWafers, 15%), Germany (Siltronic, 11%), and South Korea (SK Siltron, 11%). A summary of the Department of Commerce's Request for Information on bottlenecks in the semiconductor supply chain contributing to chip shortages in 2021 cited limited availability of silicon wafer production capacity, with no apparent short-term solutions.[73] SUMCO, a leading global supplier, indicated in 2022 that all production capacity for the most common size of silicon wafer (300 mm in diameter) was sold out through 2026.[74] Because demand for wafers is likely to increase with many announced global investments into increasing chip manufacturing capacities, supply constraints for silicon wafers may persist in the coming years. However, new wafer manufacturing capacity is also planned. In December 2022, GlobalWafers began construction on a $5 billion wafer production factory expected to begin production in 2024.

Demand for semiconductor materials is closely correlated with the locations for semiconductor manufacturing; facilities in the United States accounted for 10% of semiconductor materials demand in 2021. The locations with the highest demand for semiconductor materials were China (19%), Taiwan (19%), South Korea (17%), and Japan (16%); these are also the locations with the highest wafer fabrication capacities.[75]

Equipment

Semiconductor production requires complex equipment, including photolithography machines to print circuit patterns; etch and clean machines to remove materials; deposition and implantation machines to add new materials; diffusion machines for thermal treatments; process control equipment to ensure quality; wafer handling to transport wafers; and planarization machines to smooth out wafer surfaces. U.S.-headquartered firms lead in the producing of nearly all types of semiconductor manufacturing equipment except photolithography and wafer handling, accounting for the highest revenues in 2021 (42%), followed by Japan (27%) and Europe (21%).[76] Leading global equipment suppliers headquartered in the United States include Applied Materials, Lam Research, and KLA. Chinese and Japanese companies lead in equipment used for

[72] Most neon gas is produced as a byproduct of the steel manufacturing process; Ukraine produces a large proportion of neon gas globally from its legacy steel industry. Samantha DeCarlo and Samuel Goodman, *Ukraine, Neon, and Semiconductors*, U.S. International Trade Commission, April 2022, at https://www.usitc.gov/publications/332/executive_briefings/ebot_decarlo_goodman_ukraine_neon_and_semiconductors.pdf.

[73] U.S. Department of Commerce, *Secretary Raimondo Announces Results of Request for Information on Semiconductor Supply Chain*, January 25, 2022, at https://www.commerce.gov/news/blog/2022/01/secretary-raimondo-announces-results-request-information-semiconductor-supply.

[74] Takashi Mochizuki and Vlad Savov, "Key Supplier of Wafers for Chips Has Sold Out Through 2026," *Bloomberg*, February 9, 2022.

[75] Arizona Commerce Authority and Boston Consulting Group, *The National Semiconductor Economic Roadmap*, December 2022, p. 21, at https://web-assets.bcg.com/52/6b/7217e856495a83ac0b8447a2187e/national-semiconductor-economic-roadmap-nser-dec2022.pdf.

[76] Center for Security and Emerging Technology, *The Semiconductor Supply Chain: Assessing National Competitiveness*, January 2021, p. 26, at https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf.

wafer handling as well as packaging, assembly, and testing of semiconductors. Photolithography equipment is produced primarily in Europe (Netherlands) and Japan.[77]

Since the introduction of China's state-led semiconductor industrial policies in 2014, U.S. exports of semiconductor equipment to China have increased nearly fivefold (by over 350%).[78] China is almost completely dependent on imported equipment, although new industrial policies seek to fill this gap by funding PRC semiconductor software tools and equipment firms.[79] In October 2022, to slow the indigenous ability of China to develop and mass-produce advanced chips, BIS enacted new restrictions requiring licenses for the exports of certain semiconductor equipment and services by U.S. persons used in the production of advanced logic and memory chips in PRC facilities. According to news reports, in February 2023 the United States reached an agreement with the Netherlands and Japan to also restrict certain advanced semiconductor equipment sales to China. China's new outlays of subsidies, estimated at $143 billion over five years, are focused on covering the costs of equipment, including imports and the development of domestic firms.[80] PRC foundries such as SMIC, Huahong Group, Nexchip, and IDM Silan Microelectronics have stocked up on semiconductor equipment, including equipment from the second-hand global market that the U.S. government had restricted from being directly exported to PRC firms in China (e.g., Huawei).[81]

Photolithography Equipment

Photolithography machines are an essential component of the semiconductor fabrication process. Photolithography equipment is used to pattern billions of electronic features on a silicon wafer by using different types of light passing through a mask (similar to a stencil) onto the underlying wafer, which is covered in light-sensitive materials. As electronic features have become smaller with more advanced process nodes, smaller wavelengths of light are required. For the most advanced process nodes (e.g., 3 nm and 5 nm), extreme ultraviolet (EUV) light is primarily used to pattern circuits onto the wafer; manufacturing processes for more mature process nodes (typically above 7 nm) use deep ultraviolet (DUV) light in the patterning process. EUV photolithography equipment has taken decades of research and development to produce and is made by a single company in the Netherlands, ASML. The remaining photolithography equipment market is accounted for by ASML and firms headquartered in Japan.

[77] Center for Security and Emerging Technology, *The Semiconductor Supply Chain: Assessing National Competitiveness*, January 2021, p. 26, at https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf.

[78] U.S. Department of Commerce, Census Bureau, U.S. export data for 2014 and 2022.

[79] *Conditions for Integrated Circuit Design, Equipment, Materials, Packaging, and Testing Companies Encouraged by the State*, draft measures for comment issued by the Ministry of Industry and Information Technology (MIIT), People's Republic of China, on February 4, 2021; and *Notification of the Relevant Requirements for the Development of Lists of Projects and Software Companies, Development and Reform High Technology* [2021] No. 413, issued by the National Development and Reform Commission, MIIT, Ministry of Finance, General Administration of Customs, and General Administration of Taxation on March 29, 2021.

[80] Julie Zhu, "China readying $143 billion package for its chip firms in face of U.S. curbs," Reuters, December 13, 2022.

[81] Monica Chen and Jessie Shen, "Chinese foundries are quietly making equipment purchases," *DigiTimes Asia*, February 3, 2023, at https://www.digitimes.com/news/a20230202PD215/china-huawei-silan-microelectronics-smic.html.

Challenges for Transitioning from Research and Development to Production

Small and medium-sized semiconductor companies face challenges in securing manufacturing capacity due to the prioritization of higher-volume orders from larger businesses, according to a Commerce Department survey. In addition, startups and other entities that account for relatively small portions of semiconductor demand (e.g., national laboratories, universities, and the Department of Defense, which create semiconductor designs using innovative materials or processes) may not be able to manufacture their designs in foundries, which typically use standard processes. This is sometimes referred to as the "lab-to-fab gap," and it affects the ability of enterprises accounting for a small share of semiconductor demand to prototype and scale the manufacturing of their designs. To address this gap, an open-access foundry coordinated by the National Semiconductor Technology Center (created pursuant to provisions in the CHIPS Act of 2022) can receive co-investment from qualified participants to increase the ability of domestic entities to prototype innovative designs.[82]

According to the Commerce Department, a number of challenges are associated with commercializing semiconductor research and development and securing production capacity for chip designs. At the same time, these challenges may provide the United States with an opportunity to encourage innovation and advance national security efforts. Some challenges include the following:

- At the design phase, chips need to be manufactured in small quantities to debug and validate the design, yet foundries and advanced packaging facilities are not structured for small runs. The prototyping process requires improved access to shared infrastructure, such as multiproject wafer runs and design libraries.
- The costs of prototyping and testing designs has increased worldwide. Venture capital and other investors are reluctant to invest in projects at the early stage given the high cost, the long time required to validate that a new technology works as designed, and the resulting risk.
- The industry lacks agreement on roadmaps to guide the concurrent development of tools, materials, and manufacturing processes.
- The industry faces difficulty in attracting and retaining domestic and international research scientists in the highly competitive global market for technology talent.
- For innovations beyond design, such as new devices and materials, high development costs and long payoff times pose additional risks.[83]

These challenges are especially daunting to smaller firms and startups, potentially deterring innovation.

[82] 15. U.S.C. § 4656 (c) National Institutes of Standards and Technology, *Incentives, Infrastructure, and Research and Development Needs to Support a Strong Domestic Semiconductor Industry*, August 2022, p. 11, at https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1282.pdf.

[83] NIST, *CHIPS for America: A Strategy for the CHIPS for America Fund*, September 6, 2022.

U.S. Semiconductor Industry

According to the Semiconductor Industry Association (SIA), the United States "has been the long-standing global leader in semiconductors, with a 45% to 50% share of worldwide revenues in the last 30 years."[84] About 800 semiconductor and related device manufacturing firms were located in the United States in 2020.[85] While the U.S. semiconductor industry plays a leading role in many parts of the semiconductor supply chain (e.g., semiconductor design and equipment manufacturing), domestic semiconductor manufacturing capacities have been in decline for decades. In addition, U.S. industry has lost its leadership position over time in assembly, packaging, and test capabilities, as those functions have been offshored, primarily to Southeast Asia and China.[86] U.S. industry has also lost its leadership in memory chips through decades of state support in Japan, South Korea, and Taiwan.[87] U.S. industry currently faces growing competition from China in many parts of the supply chain, including materials, gases, and power chips, where PRC industrial policies are focused. PRC state policies are also seeking to close gaps where China depends on U.S. and other foreign firms, such as EDA software design tools and semiconductor manufacturing equipment.[88]

Some U.S.-headquartered semiconductor firms that design and manufacture in the United States have built fabrication facilities overseas. Similarly, U.S. 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 contract fabrication capacity is in Asia, primarily in Taiwan, South Korea, and China.

Six semiconductor companies currently operate 20 fabrication facilities, or fabs, in the United States. However, with the movement of many U.S. firms toward a fabless model (companies that design, but do not manufacture, semiconductors) and the outsourcing of manufacturing to companies located offshore, the share of semiconductor fabrication capacity located in the United States has experienced a long-term decline—from around 40% in 1990 to approximately 12% in 2020, according to SIA,[89] and from 26.1% in 1995 to 12.6% in 2015, according to trade

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[84] Antonio Varas et al., *Government Incentives and U.S. Competitiveness in Semiconductor Manufacturing*, Semiconductor Industry Association and Boston Consulting Group, September 2020, at https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf. Hereafter, *Government Incentives.*

[85] U.S. Census Bureau, *2020 Economic Surveys Business Patterns*, 2020, based on North American Industry Classification System code 334413 for semiconductor and related device manufacturing, at https://data.census.gov/cedsci/profile?n=334413&g=0100000US. NAICS 33413 is not inclusive of all firms involved in the semiconductor value chain, as design-only firms that outsource their manufacturing to foundries are not classified in NAICS 334413. Andre Barbe et al., "Trade and Labor in the U.S. Semiconductor Industry," U.S. International Trade Commission, *Journal of International Commerce and Economics* (July 2018), p. 6, at https://www.usitc.gov/publications/332/journals/barbe_kim_and_riker_-_trade_and_labor_in_the_us_semiconductor_industry_.pdf.

[86] U.S. GAO, *Offshoring: U.S. Semiconductor and Software Industries Increasingly Produce in China and India*, September 2006.

[87] Hideko Uno, "Japan's Semiconductor Industrial Policy from the 1970s to Today," blog post, CSIS, September 19, 2022; S. Ran Kim, "The Korean System of Innovation and the Semiconductor Industry: A Governance Perspective," Science Policy Research Unit and Sussex European Institute, December 1996, at https://www.oecd.org/korea/2098646.pdf; and Doug Fuller, *Globalization for Nation Building: Industrial Policy for High-Technology Products in Taiwan*, Industrial Performance Center, Massachusetts Institute of Technology Working Paper Series, January 2002.

[88] CRS Report R46767, *China's New Semiconductor Policies: Issues for Congress*, by Karen M. Sutter; Will Hunt, Saif M. Khan, and Dahlia Peterson, "China's Progress in Semiconductor Manufacturing Equipment: Accelerants and Policy Implications," Center for Security and Emerging Technology, Georgetown University, March 2021.

[89] The 12% share includes production by fabs in the United States by all companies, including those headquartered in

association SEMI.[90] This fabless trend has contributed to a concentration of global chip production among a handful of firms operating fabs in East Asia. Prior to enactment of the CHIPS Act of 2022, the U.S. share was projected to fall further, as planned new foreign fabs are expected to open in the next few years, particularly in East Asia.

The globalization of the semiconductor industry has involved a process of offshoring key aspects of the U.S. supply chain, including production, allowing foreign firms and markets to gain key market shares and competencies. U.S. industry is now increasingly challenged by China's ambitious state-led efforts to simultaneously build out leadership capabilities in all parts of the semiconductor supply chain. Although China is a latecomer to the sector and lags behind technologically, its capabilities are advancing rapidly, with strong state support and the ability to leverage access to China's market to require or otherwise incentivize foreign technology transfer. China has made technological strides through

- state-tied acquisitions of, and joint ventures with, foreign semiconductor firms (including firms such as AMD, Intel, and ARM, which own core IP for semiconductor chip architecture);
- technology transfer and licensing;
- an increasingly active use of open-source technology platforms for chip design and testing (e.g., RISC-V);
- talent development and research and development operations in the United States;
- efforts to attract foreign industry talent to China (particularly from Taiwan);
- IP theft; and
- capital investments and support from U.S. and foreign industry to build out China's semiconductor suppliers for key customers, such as Apple.[91]

In late 2018, Taiwan-headquartered Hon Hai Precision, or Foxconn, the key contract manufacturer for Apple, signed a deal with the PRC's Nanjing city government to build a new $282 million chip manufacturing equipment factory. Around the same time, Foxconn signed a deal with the Jinan government to jointly create a $523 million industrial fund to finance semiconductor design firms. Foxconn is also reportedly building a semiconductor packaging and testing plant in Qingdao for AI and 5G chips. The facility is co-financed with the PRC's state-backed Rongkong Group.[92] The firm has co-invested with the PRC in a chip fab for IoT, AI, and 5G chips, leveraging Sharp's semiconductor expertise—a company Foxconn acquired in 2016.[93]

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the United States and those owned by foreign firms. The data excludes capacity below 5 kpmw (thousand wafer starts per month) and wafers less than 8 inches; much of the production in the early 1990s relied on wafers smaller than 8 inches.

[90] European Semiconductor Industry Association, "Trends in worldwide semiconductor production," press release, June 17, 2021, at https://www.eusemiconductors.eu/sites/default/files/ESIA_PR_WWCapacity_2021.pdf.

[91] CRS Report R46767, *China's New Semiconductor Policies: Issues for Congress*, by Karen M. Sutter; Wayne Ma, "Inside Tim Cook's Secret $275 Billion Deal with Chinese Authorities," *The Information*, December 7, 2021.

[92] Jane Zhang, "Apple Supplier Foxconn Steps up Semiconductor Plans with Deal to Build a New Base in Qingdao," *South China Morning Post*, April 17, 2020, at https://www.scmp.com/tech/big-tech/article/3080435/apple-supplier-foxconn-steps-semiconductor-plans-deal-build-new-base.

[93] Makiko Yamizaki and Jess Macy Yu, "Foxconn to Build $9 Billion Chip Plant in China with Local Government: Nikkei," Reuters, December 21, 2018, at https://www.reuters.com/article/us-foxconn-chips-sharp/foxconn-to-build-9-billion-chip-plant-in-china-with-local-govt-nikkei-idUSKCN1OK0WQ.

These developments in China continue to heighten concerns about the competitive position of the U.S. semiconductor industry.

Planned Fabs and Supplier Facilities Locations

Sixty-one semiconductor fabrication facilities have a high probability of beginning construction from 2021 through 2023, with the most facilities located in Taiwan (15), China (14), United States (10), Europe (9), and Japan (7).[94] Of these 61 fabs, 14 are anticipated to be equipped to produce advanced nodes (below 7 nm).

Semiconductor manufacturing firms headquartered in the United States operate more than half of their fabrication capacity outside of the United States, primarily in Taiwan, Japan, Singapore, and Europe.[95] In addition, while the companies capable of producing the most advanced logic chips currently in production (3 nm node) are building additional fabs in the United States, they reportedly produce their most advanced chips in the location of their headquarters (i.e., Taiwan for TSMC and South Korea for Samsung Foundries).

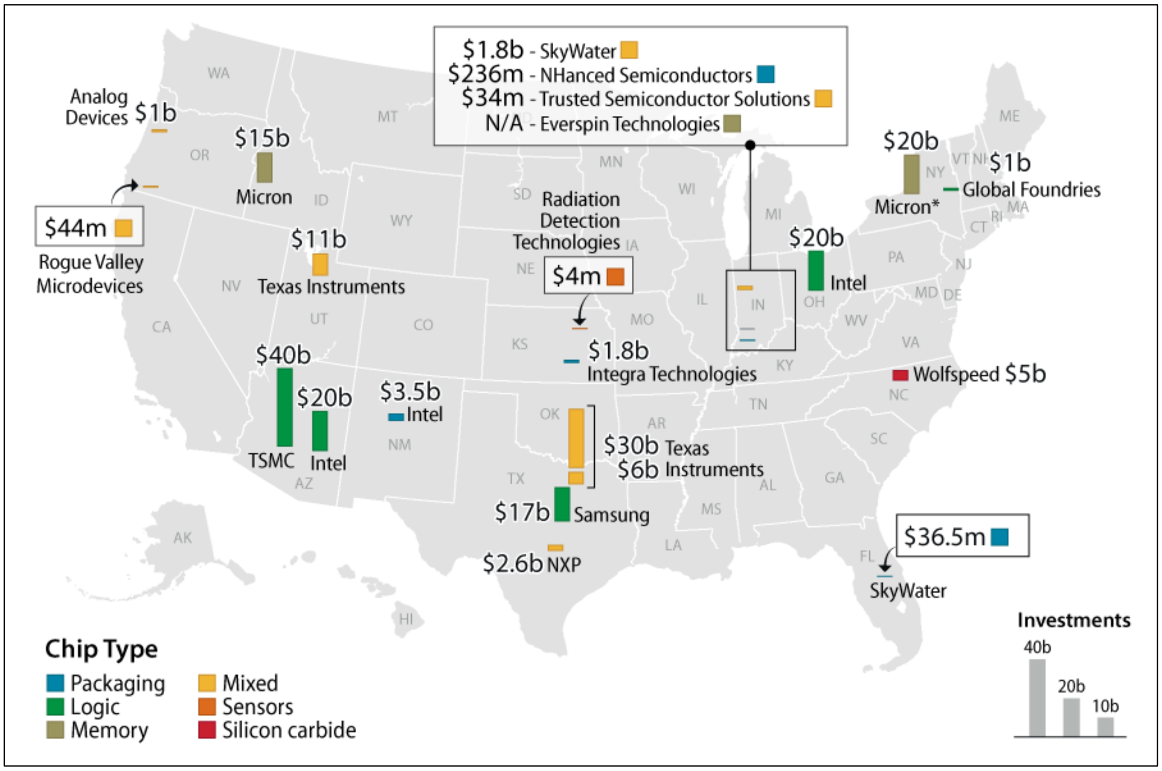
Between 2020 and 2022, U.S.- and foreign-headquartered firms announced over $200 billion in private investments to expand domestic manufacturing capacities for semiconductor fabrication, equipment, and materials across 16 states, with the largest investments announced for logic and memory chip fabrication facilities Arizona, Texas, Idaho, Ohio, and New York.[96] **Figure 3** illustrates industrial plans to expand U.S.-based semiconductor manufacturing (see **Appendix A** for list). **Figure 4** illustrates industrial plans to expand domestic facilities for suppliers of the semiconductor manufacturing industry, including for manufacturing equipment, materials, chemicals, and gases (see **Appendix B** for list).

[94] Christian Gregor Dieseldorff, SEMI, "World Fab Forecast: Trends & Forecast: Fab Equip Spending, Capacities & New Fabs," Market Symposium at Semicon West, San Francisco, CA, July 11, 2022.

[95] Semiconductor Industry Association, *2022 State of the U.S. Semiconductor Industry*, November 2022, p. 26, at https://www.semiconductors.org/wp-content/uploads/2022/11/SIA_State-of-Industry-Report_Nov-2022.pdf.

[96] Semiconductor Industry Association, *The CHIPS Act Has Already Sparked $200 Billion in Private Investments for U.S. Semiconductor Production*, March 3, 2023, at https://www.semiconductors.org/the-chips-act-has-already-sparked-200-billion-in-private-investments-for-u-s-semiconductor-production/.

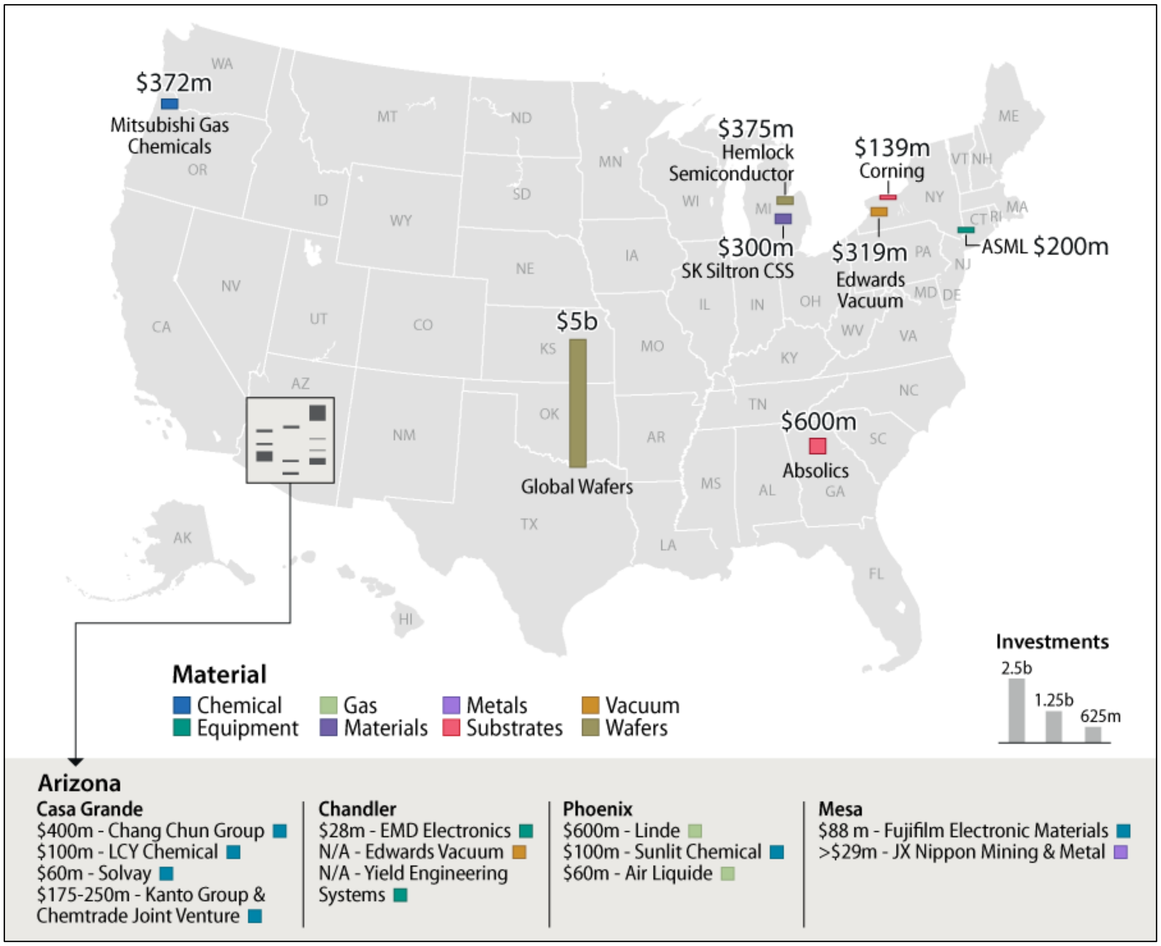
Figure 3. Map of Announced Plans to Expand Domestic Semiconductor Manufacturing



Source: CRS, using publicly available information.

Notes: The announced plans shown on this map are intended to be illustrative and not comprehensive. Not all planned investments may be made and result in actual fab construction/expansion.
* = Micron has announced $100 billion in investments into New York manufacturing facilities over the next 20-plus years; only the investment specified through this decade to 2030 is shown here.

Figure 4. Map of Announced Plans to Expand Domestic Semiconductor Manufacturing Suppliers



Source: CRS, using publicly available information.

Notes: The announced plans shown on this map are intended to be illustrative and not comprehensive. Not all planned investments may be made and result in actual facility construction.

Lead-Time for Domestic Production

Globally, fab construction on a new site (also referred to as a greenfield site) typically takes between two to four years before it is fully operational. Between 2010 and 2020, fabs constructed in the United States took two-and-a-half years on average from the start of construction to begin production. In contrast, during the same period, fabs built in the PRC and Taiwan required about 1.8 years to complete construction.[97] According to Intel executives, when discussing plans for fabs in the United States and Germany, "best-in-class" semiconductor fabs take three to five years to build after the land, construction team, and the vision for the facility are in place.[98] Preconstruction activities include design and permit approvals, followed by site development,

[97] John VerWey, *No Permits, No Fabs*, Center for Security and Emerging Technology, October 2021, pp. 6-8.

[98] Dylan Martin, "Intel: The economy is bad right now, but we still need more fabs," *The Register*, November 29, 2022.

installation of various utility and process systems (e.g., clean room and delivery systems for chemical and gases), and installation of equipment used to process wafers.

Some industry experts/analysts have pointed out that extensive permitting requirements can increase the time associated with fab construction. For example, obtaining preconstruction and operating permits required under the Federal Clean Air Act can take 12 to 18 months.[99] In addition, domestic fab construction projects that receive financial incentives under the CHIPS Act of 2022 may require review under the National Environmental Policy Act (NEPA), which applies to construction projects considered as major federal actions. Potential strategies to reduce the time associated with permitting include expedited reviews and resolution of redundant federal and state permit requirements. Other federal agencies involved in regulating environmental health and safety aspects of fab construction and operation include the U.S. Army Corps of Engineers and the U.S. Department of the Interior.

Facility Site Selection Considerations

When deciding where to locate or expand semiconductor fabrication facilities, manufacturers may consider a variety of factors:

- capital costs;
- labor availability and costs;
- regulatory environment;
- land costs;
- water, waste treatment, and electricity costs;
- energy reliability;
- transportation infrastructure;
- proximity to customers;
- political stability;
- trade barriers (e.g., tariffs and technology transfer or localization requirements);
- national security requirements (e.g., export controls, trusted foundry requirements); and
- financial incentives and subsidies offered by national, regional, and local governments.[100]

Leading-edge logic and memory chips require some of the highest fab construction costs of any type or generation of chip. The costs to construct and equip a fab producing leading-edge logic chips was around $5 billion in 2020 (5 nm node), compared with $3 billion in 2016 (7 nm node).

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[99] President's Council of Advisors on Science and Technology, *Ensuring Long-Term U.S. Leadership in Semiconductors*, January 2017, p. 17, at https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_ensuring_long-term_us_leadership_in_semiconductors.pdf.

[100] Boston Consulting Group and Semiconductor Industries Association, *Strengthening the Global Semiconductor Value Chain*, April 2021, p. 33, at https://www.semiconductors.org/wp-content/uploads/2021/05/BCG-x-SIA-Strengthening-the-Global-Semiconductor-Value-Chain-April-2021_1.pdf; National Academies Press, *Dispelling the Manufacturing Myth: American Factories Can Compete in the Global*, 1992, at https://doi.org/10.17226/1890. Kyoko Ii, *Decision Factors Affecting Semiconductor Industry Location and the Regional Advantages of Kumamoto Prefecture, Japan*, The Walter H. Shorenstein Asia-Pacific Research Center, Freeman Spogli Institute for International Studies, Stanford University, January 2008, at https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/Ii_FINAL_January_2008.pdf.

For comparison, the cost of a leading-edge fab in 1992 was approximately $500 million.[101] Because memory chips are a commoditized semiconductor product differentiated by the lowest prices, producers of memory chips typically need to construct the largest chip fabrication facilities (producing over 100,000 wafers a month) to benefit from economies of scale. Accordingly, a new memory chip factory could incur costs of more than $15 billion to construct.[102] By some estimates, the cost of equipping a fab can be about half of the total cost. Intel reports that equipment accounts for $92.7 billion (more than half) of its total of $174.3 billion in property, plant, and equipment.[103]

The cost of building and operating a fab (total cost of ownership, or TCO) is higher in the United States than it is in several Asian countries. The TCO for a fab located in the United States is approximately 25% to 30% higher than the equivalent fab located in Taiwan or Singapore, and 50% higher than a fab located in China, to a large extent due to financial support that governments offer in these markets.[104] Many countries provide incentives for the construction and operation of fabs and support the training of fab workers, which lowers the TCO for companies in those locations. An analysis by the SIA and Boston Consulting Group found that "government incentives typically reduce up-front capital expenditure on land, construction, and equipment, but they can also extend to recurrent operating expenses such as labor costs," and estimated that "government incentives can offset between 15% and 40% of the gross TCO (before incentives) of a new fab, depending on the country."[105] Further, the analysis concluded that government incentives constitute 40%-70% of the cost advantage other countries have over the United States.

Historically, the assembly, test, and packaging (ATP) sectors of the semiconductor industry have been less profitable than chip fabrication and have required more labor for less value-added activities. Accordingly, ATP functions were the first stage of semiconductor production to be outsourced and offshored to Asia beginning in the early 1970s. In 2021, ATP facilities located in the United States accounted for 5% of global ATP capacity. Facilities located in Asia accounted for more than 70% of ATP capacity, led by China and Taiwan.[106]

The United States, however, has a large share of advanced packaging capacity—nearly a quarter in 2020, and it may become a more attractive location as automation reduces the importance of

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[101] Sebastian Göke, Kevin Staight, and Rutger Vrijen, *Scaling AI in the sector that enables it: Lessons for semiconductor-device makers*, McKinsey & Company, April 2021, at https://www.mckinsey.com/industries/semiconductors/our-insights/scaling-ai-in-the-sector-that-enables-it-lessons-for-semiconductor-device-makers. For comparison, the cost of a leading-edge fab in 1992 was approximately $500 million (see National Academies Press, *Dispelling the Manufacturing Myth: American Factories Can Compete in the Global*, 1992). In 2022, the cost (in inflation-adjusted dollars) was approximately five times higher.

[102] Brian Shirley, *Don't Forget about Memory*, Potomac Institute for Policy Studies, August 24, 2022, at https://www.potomacinstitute.org/steps/featured-articles/september-2022/don-t-forget-about-memory.

[103] Intel Corp., U.S. Securities and Exchange filing, Form 10-K, fiscal year ending December 31, 2022, p. 92, at https://www.intc.com/filings-reports/annual-reports/content/0000050863-23-000006/0000050863-23-000006.pdf.

[104] The estimate of 50% higher TCO in the United States than in China does not include "additional advantages in financing costs provided by China through access to credit and equity below the cost of capital." Semiconductor Industry Association, *Government Incentives and US Competitiveness in Semiconductor Manufacturing*, September 2020, p. 18, at https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf.

[105] Ibid., p. 17.

[106] Arizona Commerce Authority and Boston Consulting Group, *The National Semiconductor Economic Roadmap*, December 2022, p. 21, at https://web-assets.bcg.com/52/6b/7217e856495a83ac0b8447a2187e/national-semiconductor-economic-roadmap-nser-dec2022.pdf.

labor costs.[107] The advanced packaging industry made up nearly half of the packaging industry by value in 2019 and is expected to gain increased market share by 2025.[108]

U.S. States Employing the Largest Number of Workers

As of September 2022, total U.S. employment in the semiconductor and related device manufacturing industry was 194,784. Employment was concentrated in a handful of states, with the top five states accounting for 69.5% of total U.S. employment in this industry, and the top 10 states accounting for 86%. California ranked first in employment in this industry, with 23.1%, followed by Texas (15.9%), Oregon (15.1%), Arizona (10.8%), and Florida (4.6%).[109] (See **Table 2** for number of employees.)

Table 2. States with the Highest Employment in the Semiconductor and Related Device Manufacturing Industry

March 2022

State	Number of Employees
California	45,087
Texas	30,924
Oregon	29,437
Arizona	20,948
Florida	9,007
Total, United States	**194,784**

Source: U.S. Department of Labor, Bureau of Labor Statistics, Quarterly Census of Employment and Wages, at https://data.bls.gov/cew.

Note: The North American Industry Classification System code for the Semiconductors and Related Device Manufacturing industry is 33413.

Considerations for Congress

The growth in federal attention and support to expand domestic semiconductor manufacturing capabilities and competitiveness, including appropriations in the CHIPS Act of 2022 (P.L. 117-167), raises a number of implementation and oversight issues for Congress. As global demand for semiconductor chips is expected to increase substantially over the next decade, from a roughly $600 billion market in 2022 to $1 trillion by 2030, the resiliency of the domestic semiconductor industry will likely remain an area of congressional interest in the future.[110]

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[107] Based on the top 10 companies, which comprised 93% of total advanced packaging capacity in 2020. Santosh Kumar, Stefan Chitoraga, and Favier Shoo, *Status of the Advanced Packaging Industry 2021*, Yole Development, September 2021, p. 66.

[108] Semiconductor Industry Association, *Trends and Challenges in Advanced Packaging*, September 29, 2020, at https://www.semiconductors.org/events/webinar-trends-and-challenges-in-semiconductor-advanced-packaging/.

[109] U.S. Department of Commerce, Quarterly Census of Employment and Wages, Employment and Wages Data Viewer, private employment, NAICS 334413 (semiconductor and related device manufacturing), at https://data.bls.gov/cew/apps/data_views/data_views.htm.

[110] Gartner, "Gartner Says Worldwide Semiconductor Revenue Grew 1.1% in 2022," press release, January 17, 2023, at https://www.gartner.com/en/newsroom/press-releases/2023-01-17-gartner-says-worldwide-semiconductor-revenue-

In this context, potential issues for Congress may include the following:

- How effective have allocations of federal financial incentives available through the CHIPS Act for domestic semiconductor manufacturing facilities been in promoting economically viable and competitive semiconductor technologies?
- Should the United States increase coordination with international partners to strengthen supply chain resilience by, for example, aligning investment priorities and developing mechanisms to monitor supply disruptions?
- What other tools, if any, should the federal government utilize to increase supply chain security for semiconductors, such as stockpiling critical materials, establishing programs for supply chain risk assessments and transparency, and monitoring demand from critical manufacturing industries?
- Are different federal strategies required for promoting technological leadership in leading-edge semiconductor nodes that require more capital investments versus strategies for ensuring supply chain security across many technology nodes, including mature chips?
- How successfully have federal research and development programs and manufacturing incentives enabled broader access to prototyping and manufacturing facilities for start-ups, universities, and small businesses?

grew-one-percent-in-2022#:~:text=
Worldwide%20semiconductor%20revenue%20increased%201.1,for%2077.5%25%20of%20the%20market; McKinsey & Company, *The semiconductor decade: A trillion-dollar industry*, April 1, 2022, at https://www.mckinsey.com/industries/semiconductors/our-insights/the-semiconductor-decade-a-trillion-dollar-industry#/.

Appendix A. Announced Plans to Expand Domestic Semiconductor Manufacturing Facilities

Table A-1.Announced Plans to Expand U.S.-based Semiconductor Manufacturing

Chip Type/Supply Chain Stage	Company	State	Fab Number and Type	Technology Generation	Investment
Logic chips	Intel	Ohio	2 new, IDM and Foundry	Leading edge	$20 billion
	Intel	Arizona	2 new, IDM and Foundry	Leading edge	$40 billion
	TSMC	Arizona	2 new, Foundry	Leading edge	$12 billion
	Samsung	Texas	1 new, IDM and Foundry	Leading edge	$17 billion
	Global Foundries	New York	Expansion, Foundry	Mature	$1 billion
Memory chips	Micron	New York	4 new, IDM	Leading edge	$20 billion
	Micron	Idaho	1 new IDM	Leading edge	$15 billion
	Everspin Technologies	Indiana	1 new	Mature	Unknown
Power Management Chips and Materials	Wolfspeed	North Carolina	1 new IDM and Foundry	Advanced materials	$5 billion
Analog, Sensors, others	Texas Instruments	Texas	4 new, 1 expansion, IDM	Mature	$36 billion
	Texas Instruments	Utah	1 new, IDM	Mature	$11 billion
	Analog Devices	Oregon	Expansion, IDM	Mature	$1 billion
	NXP	Texas	Expansion, IDM	Mature	$2.6 billion
	Radiation Detection Technologies	Kansas	Expansion, IDM	Mature	$4 million
	Rogue Valley Microdevices	Oregon	1 new, IDM	Mature	$44 million
	Trusted Semiconductor Solutions	Indiana	1 new, IDM	Mature	$34 million
Packaging/ Advanced Packaging and other services	Intel	New Mexico	Expansion, IDM and Foundry	Advanced Packaging	$3.5 billion
	SkyWater Technology	Indiana	1 new, Foundry	Advanced Packaging	$1.8 billion
		Florida	Expansion, Foundry	Packaging/ Advanced Packaging	$36.5 million

Chip Type/Supply Chain Stage	Company	State	Fab Number and Type	Technology Generation	Investment
	Integra Technologies	Kansas	1 new, Foundry	Packaging and Testing	$1.8 billion
	Nhanced Semiconduct-ors	Indiana	1 new, Foundry	Packaging/ Advanced Packaging	$236 million

Source: Compiled by CRS using publicly available information; Semiconductor Industry Associations, at https://www.semiconductors.org/the-chips-act-has-already-sparked-200-billion-in-private-investments-for-u-s-semiconductor-production/.

Notes: The information contained in this chart is intended to be illustrative and is not necessarily comprehensive. The information relies on corporate announcements of plans for fabs that may not necessarily result in actual fab construction. Based on announcements made between May 2002 and January 2023. Investments to be made over 10 years; in some cases higher amounts have been announced over a longer period.

Appendix B. Announced Plans to Expand Domestic Semiconductor Manufacturing Suppliers

Table B-1. Announced Plans to Expand U.S.-based Semiconductor Manufacturing Suppliers

Supplier Type	Company Name	State	Investment
Chemical	Chemtrade	Ohio	$50 million
Chemical	Chang Chun Group	Arizona	$400 million
Chemical	Fujifilm Electronic Materials	Arizona	$88 million
Chemical	Kanto Group and Chemtrade Joint Venture	Arizona	$175-250 million
Chemical	LCY Chemical	Arizona	$100 million
Chemical	Solvay	Arizona	$60 million
Chemical	Sunlit Chemical	Arizona	$100 million
Chemical	Mitsubishi Gas Chemicals	Oregon	$372 million
Equipment	ASML	Connecticut	$200 million
Equipment	EMD Electronics	Arizona	$28 million
Equipment	Yield Engineering Systems	Arizona	Unknown
Gas	Air Liquide	Arizona	$60 million
Gas	Linde	Arizona	$600 million
Materials	Hemlock Semiconductor	Michigan	$375 million
Materials	DuPont	Delaware	$50 million
Materials	Entegris	Colorado	$600 million
Metals	JX Nippon Mining & Metal	Arizona	>$29 million
Substrates	Absolics	Georgia	$600 million
Substrates	Corning	New York	$139 million
Vacuum	Edwards Vacuum	Arizona	Unknown
Vacuum	Edwards Vacuum	New York	$319 million
Wafers	Global Wafers	Texas	$5 billion
Wafers	SK Siltron CSS	Michigan	$300 million

Source: Compiled by CRS using publicly available information; Semiconductor Industry Associations, at https://www.semiconductors.org/the-chips-act-has-already-sparked-200-billion-in-private-investments-for-u-s-semiconductor-production/.

Notes: The information contained in this chart is intended to be illustrative and is not necessarily comprehensive. The information relies on corporate announcements of plans for facilities that may not necessarily result in actual construction. Based on announcements made between May 2002 and January 2023.

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