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US TAIWAN BUSINESS COUNCIL

U.S., Taiwan, and Semiconductors: A Critical Supply Chain Partnership

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United States, Taiwan, and Semiconductors: A Critical Supply Chain Partnership
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The Project 2049 Institute
2300 Clarendon Boulevard, Suite 703
Arlington, Virginia 22201
project2049@project2049.net
www.project2049.net

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The US-Taiwan Business Council, formed in 1976, is a non-profit, member-based organization dedicated to developing the trade and business relationship between the United States and Taiwan. Members consist of public and private companies with business interests in Taiwan.

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US-Taiwan Business Council
1700 North Moore Street, Suite 1703
Arlington, Virginia 22209
council@us-taiwan.org
www.us-taiwan.org

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Executive Summary

U.S.-China trade issues, the global pandemic, and the recent chip shortages have exposed the U.S. vulnerability to supply chain disruptions. They have demonstrated the economic and national security risk that offshore vulnerabilities pose to the United States. The U.S. has attempted to reduce this dependency by incentivizing onshoring, diversifying its manufacturing base, and making key supply chains more resilient.

The risk is clear across sectors such as healthcare and pharmaceuticals, as well as in consumer goods including food, gasoline, and basic supplies. But the risk posed by a potential supply chain disruption also holds true for another significant and strategically important industry – semiconductors.

Semiconductors are the main component in all modern electronics and are therefore a critically important segment of the global economy. Any disruptions to the semiconductor supply chain would have serious repercussions for U.S. businesses and consumers by negatively impacting the economy, severely damaging the U.S. technology sector, and hampering U.S. innovation and technology leadership.

Semiconductor supply chain disruptions could also have severe repercussions for U.S. national security and U.S. critical infrastructure. Access to cutting-edge semiconductor technologies is a key driver for the weaponry that the U.S. military needs for its defensive and offensive capabilities. Currently, Taiwan and South Korea account for 100% of installed capacity to mass produce high-end semiconductors at technologies below 7 nanometers (nm), which leaves the supply to the U.S. military vulnerable. In addition, semiconductors serve as crucial components in the communications networks and transportation systems, among others, that underpin U.S. critical national infrastructure.

Countries around the world serve as key nodes in a dispersed network of suppliers for these core building blocks of the technology that modern society has come to rely upon. The U.S. works with partners around the globe, and yet the island of Taiwan may be **the** most critical link in the entire technology ecosystem. Integrated Device Manufacturers (IDMs), which both design and produce semiconductors, play an important role in the industry — with two of the largest such companies based in the United States. However, contract manufacturers of semiconductors (known as "*foundries*") and associated companies based in Taiwan also serve as key U.S. supply chain partners. Taiwan is a significant supplier not only to leading U.S. technology firms like Apple, Texas Instruments, and Qualcomm, but also to U.S. allies globally.

The risks for disruption in the semiconductor supply chain are significant. That is true whether the source of the disruption is a natural disaster like an earthquake or typhoon, a global shock to the trading system like the COVID-19 pandemic, a disruption caused by political considerations such as a blockade or armed conflict, or by other factors. Potential risks to the semiconductor supply chain are especially acute in Taiwan, given its complex political situation and the challenges posed to it by China. Taiwan is also at risk for natural disasters, as earthquakes and typhoons are common occurrences.

There are many possible disruptions that could restrict Taiwan's ability to fully participate in the global semiconductor industry. We classify the risks of these potential disruptions into 3 categories: 1) design risks; 2) supply risks; and 3) demand risks. The biggest design risk deals with obtaining the talent to design the next generations of chips and run semiconductor fabrication plants (fabs). Supply risks include the availability of raw wafers, processing equipment, materials, water, and power. Changes in demand, either up or down, can cause major challenges for the semiconductor industry, and the recent chip shortage is a clear example of this. Pandemics, natural or manmade disasters, and geopolitical conflicts can cause any or all the disruptions mentioned above.

The U.S. companies interviewed for this report all indicated that any significant disruption in Taiwan's ability to participate in the global semiconductor industry would have severe negative consequences for their business. Taiwan companies expressed their real concerns about potential disruptions in power or water availability, but their biggest concern was aggressive action from China. They were confident that they could handle almost any disruption, with armed conflict the exception.

Even a small supply chain disruption involving Taiwan could have a ripple effect throughout the semiconductor ecosystem and would thereby negatively impact the U.S. economy and potentially U.S. national security. More will need to be done to encourage and strengthen the U.S. semiconductor industry position. Future investments in leading-edge technology for the U.S. market — incentivized with government funding — should help bend the curve slightly. However, it will likely take significant time and massive investments to realize a positive outcome. The CHIPS and Science Act is a good first step in supporting the U.S. semiconductor industry and will help strengthen the overall U.S. position in the crucial semiconductor sector.

Companies in the global semiconductor supply chain are already making contingency plans for the types of disruptions laid out in this report. They are determining the best course of action to build redundancy into their operations and making plans to address issues such as lack of access to water and power, even if some disruptions – such as a global pandemic or armed conflict – might be unavoidable due to their systemic nature.

Almost any action taken to make the U.S.-Taiwan semiconductor supply chain more resilient will likely be seen as a threat to China. How China reacts to that supposed threat is hard to predict. The decision made by Taiwan Semiconductor Manufacturing Company (TSMC) to build factories in the U.S. and Japan certainly is a positive step from the U.S. point of view, because it will enhance the availability of chips at high technology levels. The fact that several Taiwan material suppliers are setting up significant facilities in Arizona also helps both TSMC and U.S.-based semiconductor manufacturers.

New capacity that is currently being built outside of Taiwan could help mitigate some of the short-term or medium-term costs of any disruptions, no matter the cause. Yet the complexity of the semiconductor industry and high costs of investing in new production capacity means it would be impossible to replace Taiwan-made chips overnight. In fact, it would be nearly impossible to replace Taiwan-made chips over several years. This means Taiwan will continue to be an essential link in the semiconductor supply chain for the foreseeable future, even as new manufacturing capacity comes online in the U.S. and around the world. The United States must therefore do everything it can to ensure that Taiwan remains a close ally.

Introduction

Integrated Circuits (IC's) were first developed in the late 1950's. They consist of a set of electronic circuits located together on one small flat piece (or "*chip*") of semiconductor material.[1] Since their introduction, IC's — often referred to simply as "semiconductors" — have changed the world.

These micro-sized building blocks to all electronic devices have become essential in our increasingly digital lives. From computer screens to vehicles, demand for semiconductor devices and chips is not only increasing, but the demand for greater performance from these chips is increasing as well. Many countries have varying capacity to develop semiconductors, but not all chips are created equal. Some chips are developed to store data while others may be developed to process data. The demand for chips affects not just the method by which these chips are created but the complexity of the production process as well.

Over the past four decades, the semiconductor industry has experienced rapid growth and delivered enormous and positive economic impact to the U.S. and the rest of the world. The semiconductor market grew at a 7.5% compound annual growth rate from 1990 to 2020, outpacing the 5% growth of global Gross Domestic Product (GDP) during that time.

An estimated additional US$3 trillion in global GDP from 1995 to 2015 has been directly linked with semiconductor innovation, with an incremental US$11 trillion in indirect impact.[2] Upcoming advances in Artificial Intelligence (AI), augmented/virtual reality, smartphones, and autonomous vehicles will require further advancements in semiconductor technology.

According to the Semiconductor Industry Association, the U.S. semiconductor industry is the worldwide industry leader with a nearly 48% market share and sales of US$275.0 billion in 2022.[3] In 2021, there were around 277,000 direct semiconductor jobs in the U.S. semiconductor industry. Each direct job supports 5.7 jobs in other parts of the U.S. economy for a total over 1,852,000 total jobs. Most of these are also high paying jobs.[4] These jobs span the breadth of the U.S., with at least 18 states being home to major semiconductor manufacturing facilities.

Semiconductor technology has made virtually all sectors of the U.S. economy — from farming to manufacturing — more effective and efficient and is the number one contributor to labor productivity growth. Semiconductors are a top 5 U.S. export, and more than 80% of U.S. semiconductor sales are to overseas customers. The U.S. exported US$61.1 billion in semiconductors in 2022.[5] The U.S. has also had a consistent trade surplus in semiconductors, including with major partners such as China.

Advanced semiconductors play an important role in driving advances in U.S. defense and military capabilities. This is increasingly true as the U.S. military posture relies on relatively few high-quality systems that are underwritten by advanced microelectronics. Visibility into the semiconductor supply chain for military systems is low, but it is telling that the Pentagon lists microelectronics as one of its top research and engineering priorities.

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[1] Materials that conduct electricity (like metals) are called conductors, while materials that do not conduct electricity (like ceramics) are called insulators. Semiconductors are substances with properties somewhere between the two. Semiconductors can consist of pure elements, such as silicon or germanium, or of compounds such as gallium arsenide. Silicon is currently the most common semiconductor used for IC's.

[2] "Moore's Law Impact," HIS Technology Report, May 2015

[3] "SIA 2023 Factbook," *Semiconductor Industry Association*, May 8, 2023, https://www.semiconductors.org/wp-content/uploads/2023/05/SIA-2023-Factbook_1.pdf

[4] "Chipping In: The Positive Impact of the Semiconductor Industry on the American Workforce and How Federal Industry Incentives Will Increase Domestic Jobs," *Oxford Economics & Semiconductor Industry Association*, May 19, 2021, https://www.semiconductors.org/wp-content/uploads/2021/05/SIA-Impact_May2021-FINAL-May-19-2021_2.pdf

[5] "SIA 2023 Factbook," op. cit.

Advanced semiconductors also play a key role in many sectors identified by the U.S. government as part of its critical infrastructure – the assets essential to keep society functioning. Such sectors include telecommunications, energy, transportation, manufacturing, and financial services.

Two locations - Taiwan and South Korea - currently hold an almost complete majority of the capacity to manufacture the most technologically advanced types of semiconductor devices. And while only a few countries excel at the near-leading-edge manufacturing process, chips manufacturing is in fact one of the most diverse supply chains in the world. Between the design, machine and chemical production, wafer fabrication, assembly, packaging, testing, and down-stream application, by some estimates a chip product could cross as many as 70 borders before it ever makes its way into consumers' hands.[6] While this global diversification is one of the leading reasons why chip production has been able to make so many advancements, there are concerns among policymakers around the globe that this interconnectedness can also add unwanted risk into the semiconductor supply chain.

Taiwan is one of the world's leaders in advanced semiconductor manufacturing. This means it's important for the U.S. and other global economies. But it is also located in a risky area, where natural disasters like typhoons and earthquakes are a common occurrence. Changes in weather have led to water shortages and increased demand on Taiwan's energy infrastructure. There is also the increasing hostility from the People's Republic of China towards Taiwan.

What would happen if the U.S. were no longer able to have access to Taiwan-made chips? What sort of effect would this have on the U.S. economy? By some rough estimates, a loss of access to Taiwan-made chips could be a 5 to 10% hit to U.S. gross domestic product.[7] In this report, we will try and estimate the value of the Taiwan semiconductor industry to the U.S. economy, and what sort of impact there would be if the U.S. could no longer have access to those chips.

We base our estimate on what a significant disruption to the Taiwan semiconductor supply chain could mean for those U.S. industries that rely heavily on the continuous and timely delivery of semiconductor devices: computer and electronic products, motor vehicles, broadcasting and telecommunications equipment, and electronic devices used for national defense. While other industries and sectors would also be affected, a significant shock to the delivery of chips to these four industries, and the halting of production and sales, could have an impact as large as either of the two previous economic recessions in the U.S.: the global financial crisis (2009) and the global pandemic (2020).

[6] Alam, Syed, et al. "Globality and Complexity of the Semiconductor Ecosystem," *Global Semiconductor Alliance and Accenture*, February 2020, https://www.accenture.com/_acnmedia/PDF-119/Accenture-Globality-and-Complexity-Semiconductor-POV.pdf

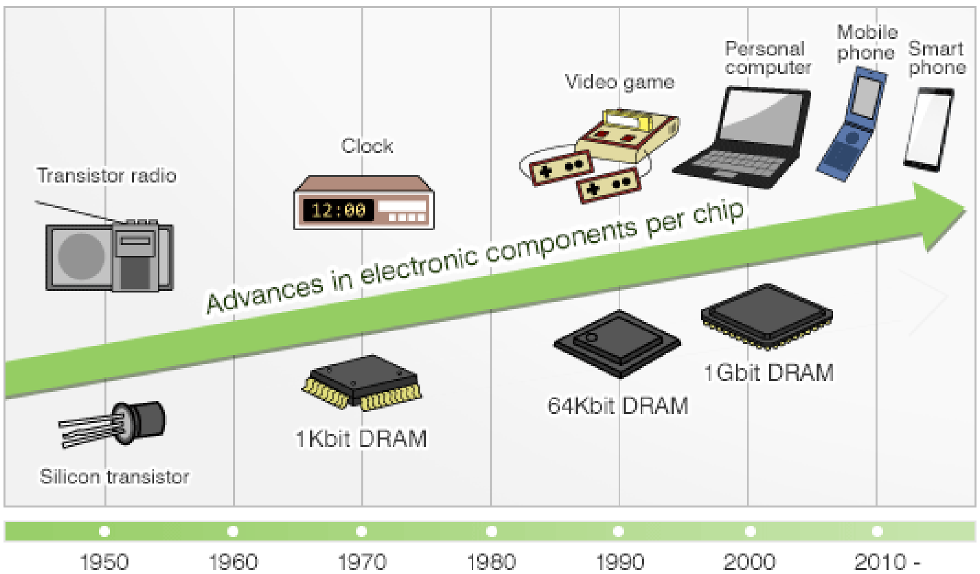
[7] "In Conversation with Ken Griffin," *Bloomberg New Economy, YouTube*, November 2022, https://www.youtube.com/watch?v=8bgF6N2T130

Background

Semiconductors continue to fuel the ever-increasing rate of innovation in communications, computing, consumer electronics, healthcare, transportation, and defense. One of the keys to continuing the rate of innovation is *Moore's Law*, a theory which states that the number of transistors on a dense IC doubles every two years.[8]

Fitting ever more transistors on an IC means that semiconductor devices are becoming smaller, faster, more energy efficient, and potentially cheaper. This law has roughly held true over the last 40 years and has led to increasingly sophisticated electronics products being introduced into the marketplace.

Figure 1: Advances in Electronic Components Per Chip



Source: Hitachi High-Tech Corporation[9]

The birth of semiconductors can be traced back to the invention of the rectifier (an AC-DC converter) in 1874, and to the two-electrode vacuum tube rectifier in 1904. Vacuum tubes played an important role in early electronics development, but it would take the calculation requirements of World War II to really push the nascent electronics field forward. In 1946, the University of Pennsylvania built a computer (ENIAC) using vacuum tubes, but their device required an entire building and demanded a large amount of electricity.

Bell Laboratories in the U.S. invented the point-contact transistor in 1947, and American physicist and inventor William Shockley invented the junction transistor in 1948. These two inventions heralded the arrival of the transistor era, which eliminated the need to use vacuum tubes. Transistors were able to replicate both the amplification and electronic switch capabilities of the vacuum tube. Replacing large, physical tubes with transistors also made electronics smaller, less hot, and not so expensive.

The semiconductor industry grew rapidly following the invention of the transistor. In 1957, the industry already

[8] "Moore's law," *Wikipedia*, https://en.wikipedia.org/wiki/Moore%27s_law

[9] "History of semiconductors," *Hitachi High-Tech Corporation*, https://www.hitachi-hightech.com/global/products/device/semiconductor/history.html

exceeded the scale of US$100 million a year. In 1959, Texas Instruments and Fairchild Semiconductor in the U.S. invented the bipolar integrated circuit, and in 1967 Texas Instruments developed an electronic desktop calculator that used IC's. Electronic equipment manufacturers in Japan began releasing calculators one after another, and fierce "calculator wars" continued until the end of the 1970's. This kickstarted an era of innovation, contributing to the continued development of IC's.

In the 1960's and 1970's, U.S. companies were the clear leader in the semiconductor industry, holding more than 50% of worldwide semiconductor sales. However, the U.S. semiconductor industry experienced a significant loss in global market share during the 1980's. Due to intense competition from Japan-based firms, significant investment by the Japanese government, the effect of illegal "dumping, "and a severe industry recession 1985 to 1986, the U.S. industry lost a total of nineteen worldwide market share points.

At the end of this period, the U.S. had ceded global industry market share leadership to the Japanese semiconductor industry.[10] The U.S. was also losing market share in the semiconductor manufacturing equipment space. Tariffs were imposed by both countries, and two trade agreements were signed (and quickly broken). There was considerable debate in the U.S. during this time as to how much the U.S. should invest to bolster the semiconductor industry as well as the role of tariffs in helping support the domestic industry. There was also considerable discussion about the importance of being on the leading edge of technology for national security. These debates continue to this day.

SEMATECH — a Research & Development (R&D) consortium jointly funded by 14 U.S. semiconductor manufacturers and the U.S. Department of Defense via the Defense Advanced Research Projects Agency (DARPA) — was formed in 1987. DARPA was concerned about keeping the U.S. domestic capability to produce the semiconductor devices needed for their advanced weapon systems. In addition to focusing on improving market share, SEMATECH focused on helping the U.S. semiconductor manufacturing equipment suppliers survive. Over the next decade, the U.S. was able to regain the lead in semiconductor market share and have held it since. The U.S. was also able to improve the position of the U.S. semiconductor equipment supplier base (with the notable exception being photolithography equipment).

During this time, the governments of three countries in the Asia Pacific region (Singapore, South Korea, and Taiwan) began to invest significant funds in the semiconductor sector. Like Japan before them, South Korea mostly focused on producing memory products. Taiwan instead mostly focused on providing contract manufacturing ("foundry") services for companies without manufacturing facilities of their own. Singapore also focused much its efforts on the foundry business but has never had a large market share. Note, however, that that South Korea's foundry market share has increased significantly over the last several years.

Taiwan's most successful foundry business is Taiwan Semiconductor Manufacturing Company (TSMC), founded in 1987 as a joint venture between the Taiwan government, Dutch multinational electronics giant Philips, and other private investors. In fact, TSMC founder Morris Chang originated the very successful foundry business model, where the design and production of semiconductors are not necessarily conducted by the same company. This shift pushed much of the capital intensity associated with manufacturing to the foundries, allowing so-called "fabless" companies to design products and invest in R&D rather than in wafer fabrication facilities.

In 2021, global semiconductor industry sales achieved a remarkable year-on-year growth rate of 26.2%.[11] According to

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[10] SIA 2021 Factbook," *Semiconductor Industry Association*, https://www.semiconductors.org/wp-content/uploads/2021/05/2021-SIA-Factbook-FINAL1.pdf

[11] "Global Semiconductor Sales, Units Shipped Reach All-Time Highs in 2021 as Industry Ramps Up Production Amid Shortage," *Semiconductor Industry Association*, February 15, 2022, https://www.semiconductors.org/global-semiconductor-sales-units-shipped-reach-all-time-highs-in-2021-as-industry-ramps-up-production-amid-shortage/

the SIA 2023 Factbook, semiconductor sales were US$570 billion worldwide in 2022, up from US$139 billion in 2001. The U.S. had a 48% market share in 2022, South Korea had 19%, the E.U. and Japan each had 9%, Taiwan had 8%, and China had 7%.[12] The global semiconductor industry increased capacity by 7.2% in 2022, with capacity increasing by 4.8% in 2023 and capacity growth expected to continue in 2024.[13]

While the U.S. holds a large market share, a significant portion of that market share is from fabless companies that mostly use Taiwan foundry services. For example, in 2021 the top three fabless companies that publicly disclose earnings (Broadcom, Qualcomm, and NVIDIA – all U.S.-headquartered companies) had combined revenues of US$61.8 billion, which would be approximately 11% of total global semiconductor revenues at that time.[14] All three of these companies rely heavily on Taiwan foundries to produce their chips.

Other important U.S. technology companies are also working extensively with Taiwan foundry companies. As an example, Apple is thought to consume more than 50% of TSMC's capacity for chip production at 5 nm (currently one of the most advanced mass-production technologies) and has signed a contract for TSMC to produce chips at 3 nm.[15] [16] For Apple, this will allow for smaller, faster, and more energy efficient semiconductor devices that will drive the next generation of iPhones and iPads, as well as any future MacBook or MAC systems that the company launches with its own proprietary designs.

[12] "SIA 2023 Factbook," op. cit.

[13] "Global fab equipment spending to see strong recovery in 2024 after a weak 2023," *New Electronics*, March 24, 2023, https://www.newelectronics.co.uk/content/news/global-fab-equipment-spending-to-see-strong-recovery-in-2024-after-a-weak-2023/

[14] "Gartner Says Worldwide Semiconductor Revenue Grew 25.1% in 2021, Exceeding US$500 Billion For the First Time" *Gartner*, January 19, 2022, https://www.gartner.com/en/newsroom/press-releases/2022-01-19-gartner-says-worldwide-semiconductor-revenue-grew-25-point-one-percent-in-2021-exceeding-500-billion-for-the-first-time

[15] Jeet, "Apple to account for 53% of TSMC 5nm chips production in 2021," *gizmochina.com*, February 8, 2021, https://www.gizmochina.com/2021/02/08/apple-tsmc-5nm-chips-2021/

[16] Chang, Eric, "TSMC secures Apple contract for its 3 nm process chips," *Taiwan News*, https://www.taiwannews.com.tw/en/news/4084966

Semiconductor Supply Chains

Semiconductor devices are highly complex products to design and manufacture. In a 2021 report, the Semiconductor Industry Association (SIA), states that the semiconductor supply chain "*consists of four broad steps, supported by a specialized ecosystem of materials, equipment and software design tools and core IP suppliers*."[17] The four broad steps are: 1) Pre-competitive research; 2) Design; 3) Frontend manufacturing (wafer fabrication); and 4) Backend manufacturing (assembly, packaging, and testing).

Overview of Supply Chain Elements

Pre-competitive research focuses on identifying fundamental materials and chemical processes and to make innovations in design architectures that will enable the next commercial leaps in computing power and efficiency. Much of this basic research is done at universities and is supported by government funding. Pre-competitive research is then followed by industrial research, which helps translate the new innovative ideas into practice — although direct benefits are often not realized for 10+ years. Pre-competitive research accounts for approximately 15-20% of overall semiconductor industry investment in most of the industry-leading countries.

Design means developing the architecture for integrated circuits. While computer chips were originally designed manually, that is not possible for the complex chips produced today. Instead, current chip design work relies on sophisticated Electronic Design Automation (EDA) software and reusable architectural building blocks. Even with these tools, developing leading-edge chips can take several years and requires the work of hundreds of design engineers. Design accounts for approximately 65% of total industry R&D expenditure.

Frontend manufacturing starts with a wafer made of raw silicon (or other semiconductor material). The electronic circuitry is fabricated onto the wafer layer by layer in a wafer fabrication facility (wafer fab). Multiple chips — typically 200-4,000 depending on the type of chip — are produced on each wafer. The heart of a wafer fab is the cleanroom. This is a sterile environment, as even a tiny dust particle on a wafer can destroy the intricate circuitry of a chip. Cleanrooms require sophisticated air handling and filtering systems to minimize contamination, and in fact cleanrooms are orders of magnitude cleaner than a hospital operating room. Processing steps during Frontend manufacturing include Oxidation, Lithography, Doping, Material Deposition, and Etching. Each of these steps is repeated many times, with some products requiring up to a total of 1,400 steps. The final step in the Frontend is to probe the wafers to determine which of the individual chips (in this context called "*die*") are up to specifications.

Frontend processing is very capital-intensive, comprising approximately 64% of industry-wide capital expenditures. Some current generation lithography tools cost at least US$150 million each, with newer and more advanced tools at well above US$340 million each.[18] Building and equipping a state-of-the-art wafer fab of standard capacity requires an investment of approximately US$10-20 billion. These plants also require top notch engineering support, so wafer fabs are generally built where there is a strong supply of engineering talent at the BS, MS, and PhD levels.

Backend manufacturing begins by slicing the wafers produced in the Frontend processes into individual chips. The chips that were determined to be good in the Frontend are then assembled and packaged into protective frames (plastic or ceramic) and encased in a resin shell to become usable in electronic devices. Finally, the chips are thoroughly tested to determine their operating characteristics (e.g. the speed for a microprocessor). The finished chips are then sent to a warehouse or are forwarded to an electronic device manufacturer or distributor.

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[17] Varas, Antonio, Varadarajan, Raj, Goodrich, Jimmy, and Falan Yinug, "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era," *Semiconductor Industry Association*, April, 2021, https://www.semiconductors.org/strengthening-the-global-semiconductor-supply-chain-in-an-uncertain-era/

[18] Sterling, Toby, "Intel orders ASML system for well over US$340 mln in quest for chipmaking edge," *Reuters*, January 19, 2022, https://www.reuters.com/technology/intel-orders-asml-machine-still-drawing-board-chipmakers-look-an-edge-2022-01-19/

While Backend processing requires sophisticated equipment, it is not as capital-intensive as the Frontend, accounting for 13% of industry-wide capital expenditures. Backend processing has traditionally been more labor intensive, and therefore these facilities are typically in countries with relatively inexpensive labor.

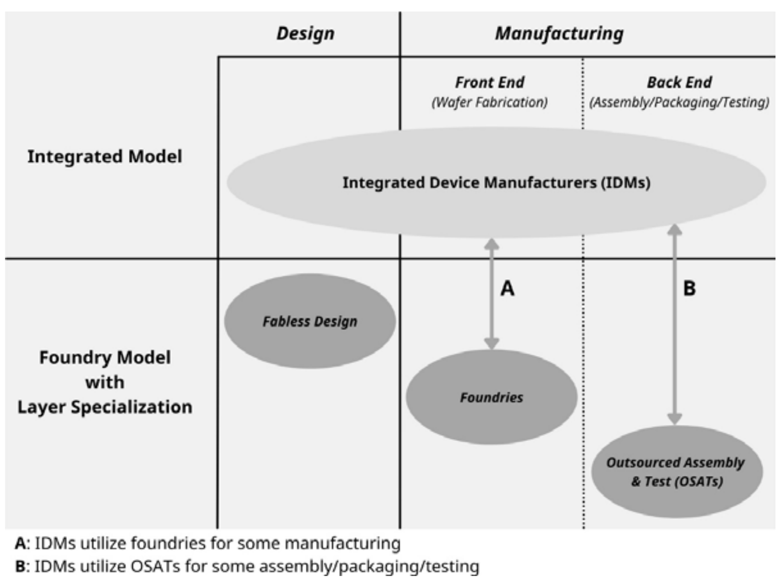
As indicated above, the semiconductor supply chain has a highly specialized upstream support ecosystem. The Design step is supported by Electronic Design Automation (EDA) software and services, as well as by reusable components designs (called IP blocks) that have a defined interface and functionality. The Frontend and Backend steps are supported by wafer processing equipment and sophisticated testing equipment. There are over 50 different types of equipment used in semiconductor manufacturing. In addition, the Frontend and Backend steps are also supported by specialized materials suppliers, including specialty chemicals.

Semiconductor Business Models

In the early days of the semiconductor industry, firms would both design their products and manufacturing equipment as well as perform both the Frontend and Backend operations, often on the same site. As the complexity of the devices and resulting processes increased, and as the demand for chips grew, many firms began to move their Backend operations to places where labor was cheap (e.g. Asia). In addition, an equipment supplier base began to emerge to support the industry, allowing firms to concentrate on their core competencies of chip design and chip manufacturing.

Increasing technology complexity and a need for economies of scale — to afford the massive investments necessary to keep the pace of innovation in both design (in the form of R&D) and manufacturing (in the form of capital expenditure) — favored the emergence of specialized players. Today, semiconductor companies may focus on one layer of the supply chain or may integrate vertically across several layers. No company, nor even an entire nation, is currently vertically integrated across all layers at once. Four types of semiconductor companies have emerged, with each classified depending on their level of integration and its business model: Integrated Device Manufacturers (IDMs), Fabless design firms, Foundries, and Outsourced Assembly and Test Companies (OSATs).

Figure 2: Semiconductor Business Models



IDMs are vertically integrated, and generally do design, wafer fabrication, and assembly/packaging/testing in-house. However, IDMs may outsource some of their production and assembly operations, e.g. for products that are near the end of life. The IDM model was predominant in the early days of the industry, but the rapidly increasing size of the market and the amount of investment needed in both R&D and capital expenditures led to the emergence of the fabless-foundry model. Most IDMs in Asia focus on memory, while there is a mix in the United States. Intel and Micron are examples of U.S.-based IDM's; Intel predominantly focuses on logic chips, while Micron focuses on memory. Other IDMs in the U.S. focus on other product types like analog devices. Together, IDMs were responsible for approximately 58.44% of global semiconductor sales as of 2021.[19]

IC production facilities are expensive to build and maintain. Unless they can be kept at nearly full utilization, they become a drain on the finances of the company that owns them. The fabless-foundry model became popular in the late 1990's and early 2000's. Under this model, fabless firms design their own products but outsource fabrication to foundries and outsource their assembly and packaging operations to OSATs. They may also outsource testing or may choose to do all or a portion of testing internally.

Qualcomm, Broadcom, and Nvidia are examples of fabless companies, and this class of companies can bypass the huge expenditures necessary to build in-house manufacturing capacity. In addition to providing great value for companies, this model has significantly reduced the barriers to entry for startup companies — important in supporting emerging leading-edge applications in AI and high-performance computing, for example. The fabless-foundry model has grown rapidly more important, with total semiconductor sales accounted for by fabless firms increasing from less than 10% in 2000 to almost 35% in 2022.[20]

Foundries supply the fabrication needs for fabless firms, as well as in some cases supplementing the capacities of IDMs. While we refer to this overall business model as the fabless-foundry model because the design comes before manufacturing, the emergence of this model was led by TSMC, United Microelectronics Corporation (UMC), and other Taiwan companies. These foundries have greatly facilitated the emergence of fabless companies. Most foundries are focused purely on manufacturing for third parties (so called "pure play" foundries), although some IDMs with strong manufacturing capabilities may also choose to make chips for others in addition to producing their own. For example, Intel has recently begun offering foundry services.[21]

Foundries have added 60% of the incremental capacity in the industry for non-memory products during the past five+ years, and currently foundries account for 35% of total industry manufacturing capacity.[22] This percentage is much higher for leading-edge products that must be produced on an advanced (7 nanometers or below) node. Currently, only TSMC and Samsung manufacture successfully at the leading 5 nanometer node.[23]

OSATs provide assembly, packaging, and testing services under contract to both IDMs and fabless companies. This section of the model emerged to support the IDMs and their need for lower skilled and cheaper labor. Foreign governments also invested in OSAT companies, and the emergence of the fabless-foundry model significantly increased the need for specialized OSAT companies.

ASE (Taiwan), Amkor (U.S. headquartered with most manufacturing in Asia), JCET (China), and SPIL (Taiwan) are

[19] "Global Semiconductor Sales, Units Shipped Reach All-Time Highs in 2021 as Industry Ramps Up Production Amid Shortage," *Semiconductor Industry Association*, February 14, 2022, https://www.semiconductors.org/global-semiconductor-sales-units-shipped-reach-all-time-highs-in-2021-as-industry-ramps-up-production-amid-shortage/

[20] "Fabless Suppliers Hold Record 34.8% Share of Global IC Sales," *Design & Reuse*, July 8, 2022, https://www.design-reuse.com/news/52302/fables-system-versus-idm-company-ic-sales.html

[21] "Intel's first foundry customers include Qualcomm and AWS," *ZDnet.com*; Stephanie Condon, July 26, 2021, https://www.zdnet.com/article/intels-first-foundry-customers-are-qualcomm-and-aws/

[22] "World Fab Forecast (WFF)," *SEMI*, December 14, 2021, https://www.semi.org/en/products-services/market-data/world-fab-forecast

[23] However, Intel claims parity with these processes, and every company measures their nodes differently.

the four largest OSAT companies by revenue, and the sector continues to grow - experiencing a 35% year over year increase in the second quarter of 2021.[24] The OSAT market is projected to grow at a Compound Annual Growth Rate (CAGR) of 3.97% between 2023–2030.[25]

Geographic Distribution

The semiconductor supply chain is truly global, with six major areas contributing significantly to the total value added to the global economy by the semiconductor industry in 2022. The U.S. had a 48% market share in 2022, South Korea had 19%, the E.U. and Japan each had 9%, Taiwan had 8%, and China had 7%.[26]

The dispersal of the supply chain somewhat reflects the geographic distribution of the industries that are major consumers of semiconductors. For example, the U.S. is the global leader in the design of electronic devices; Taiwan and China are global leaders in assembling consumer electronic devices, smartphones, and PCs; Japan and Europe are global leaders in automotive and industrial automation equipment; and South Korea is a global leader in cell phones and large consumer electronics.

The 2021 State of the U.S. Semiconductor Industry report by the Semiconductor Industry Association indicates that three additional factors contribute to the geographic distribution of the semiconductor supply chain: global R&D networks, geographic specialization, and trade liberalization.[27]

Global R&D Networks

A significant portion of R&D investment by the semiconductor industry is in fundamental research into science breakthroughs, invested many years ahead of a potential commercial application. Semiconductor companies have worked with universities and government-funded advanced science labs to collaborate on pre-competitive research to share the costs of research and avoid duplication of efforts.

China and the U.S. are the top two countries when it comes to scientific publications related to semiconductors filed in the past 10 years. Many such papers are co-authored by researchers in other countries, however, including Taiwan, South Korea, and Germany. In addition, the semiconductor industry has created or is a core contributor to a number of organizations that bring together global companies, universities, and research institutions to support international collaboration in R&D — such as IMEC in Belgium, CEA-Leti in France, and A*STAR in Singapore.

Some of the most critical recent advancements in semiconductor technology were the result of several decades of global R&D collaboration. This collaboration led to the development of the Extreme Ultraviolet Lithography (EUV) technology that enables the manufacture of semiconductors below 7 nanometers. The development of this technology started in the 1980's with fundamental research done in the U.S. and Japan, and researchers from the Netherlands became involved in the 1990's and early 2000's. ASML, a company based in the Netherlands, worked with IMEC, Intel, TSMC, and Samsung to incorporate the technology into commercially available machines by 2018. A current generation EUV machine costs US$150 million or much more, is about the size of a large bus, and contains about 100,000 parts provided by over 5,000 suppliers spread across the globe.

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[24] "Revenue of leading outsourced semiconductor assembly and test (OSAT) companies from 2019 to 2021, by quarter," *statista.com*, https://www.statista.com/statistics/1120619/leading-global-osat-companies-revenues/

[25] "2023 Global 'Outsourced Semiconductor Assembly and Test (OSAT) Market' An In-depth Analysis and Forecast of Industry till 2030," *MarketWatch*, May 24, 2023, https://www.marketwatch.com/press-release/2023-global-outsourced-semiconductor-assembly-and-test-osat-market-an-in-depth-analysis-and-forecast-of-industry-till-2030-2023-05-24

[26] "SIA 2023 Factbook," op. cit.

[27] "2021 State of the U.S. Semiconductor Industry," *Semiconductor Industry Association*, https://www.semiconductors.org/wp-content/uploads/2021/09/2021-SIA-State-of-the-Industry-Report.pdf

Geographic Specialization

The six regions mentioned above have strengths in different parts of the semiconductor supply chain. While the U.S. was once the leader in all aspects of the industry, over time this has changed. Today, the U.S. is still the leader in intensive R&D activities, while the bulk of manufacturing is conducted in Asia.[28]

Many of the top universities in the world in terms of semiconductor manufacturing research are in the U.S. While many of the graduate student researchers are foreign born, more than 75% stay in the U.S. after graduation. China has been heavily investing in semiconductor R&D, and produces more academic research papers and patents than the U.S. However, the average number of citations per U.S. semiconductor patent is between three and six times higher than for patents from any other country in the world.

U.S. IDMs and fabless companies are still the leaders in chip design, with 10 of the top 20 semiconductor design companies (including both fabless and IDMs) headquartered in the United States. About 50% of the engineers employed by the top global semiconductor companies involved in design are in the U. S., and this figure includes engineers from both U.S. and non-U.S. firms. An important result derived from R&D is the development of advanced semiconductor manufacturing equipment. In 2021, the United States held a 40.9% share of this market, followed by Japan with 29.4%, South Korea with 4.8%, and the rest of the world with 22.6% (with much of the European share from ASML in the lithography space).[29]

When it comes to wafer fabrication, four regions in Asia make up the bulk of the manufacturing capacity. In 2021, the U.S. was down to an 11% share, with Taiwan at 21%, South Korea at 23%, Japan at 15%, China at 16%, Europe at 5%, and other countries at 9%.[30] The growth of wafer fabrication capabilities in Asia was primarily due to decades-long government investment strategies and incentives. In Taiwan, the government first supported acquisition of semiconductor technology from abroad through the Industrial Technology Research Institute (ITRI). The government also helped with initial funding as ITRI spun off its first commercial semiconductor company, UMC, in 1980. The Taiwan government was similarly a significant investor – together with Dutch company Philips Electronics – in TSMC when the company was formed in 1987.[31] Taiwan has also offered numerous incentives related to land, facilities, and equipment that together with refundable investment tax credits drove the growth of the semiconductor industry on the island. The Semiconductor Industry Association has estimated that the total cost of ownership of a new fab in the U.S. is 25-50% higher than in Asia, with 40-70% of the difference due to direct government incentives.[32]

Taiwan firms also pioneered the foundry model and begun to specialize in manufacturing the chips designed by firms from other regions. The specialization has driven Taiwan leadership in the foundry segment. Today Taiwan is home to two of the five largest global foundries and hosts 20% of the total global semiconductor capacity.[33] It is also important to note that only TSMC and South Korea's Samsung are currently manufacturing chips at the leading edge of 5 nanometers and below.

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[28] See Exhibit 14 in "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era" report, op.cit., for a detailed breakdown.

[29] Thadani, Akhil and Gregory C. Allen, "Mapping the Semiconductor Supply Chain: The Critical Role of the Indo-Pacific Region," *Center for Strategic & International Studies*, May 30, 2023, https://www.csis.org/analysis/mapping-semiconductor-supply-chain-critical-role-indo-pacific-region

[30] "China's share of global wafer capacity continues to climb," *Knometa Research Corp*, February 10, 2022, https://knometa.com/news/?post=china-039-s-share-of-global-wafer-capacity-continues-to-climb

[31] "Securing the Future: Regional and National Programs to Support the Semiconductor Industry," *National Academies of Sciences, Engineering, and Medicine, The National Academies Press*, 2003, https://doi.org/10.17226/10677

[32] Varas, Antonio, Varadarajan, Raj, Goodrich, Jimmy, and Falan Yinug, "Government Incentives and US Competitiveness in Semiconductor Manufacturing," *Boston Consulting Group*, September 16, 2020, https://www.bcg.com/publications/2020/incentives-and-competitiveness-in-semiconductor-manufacturing

[33] "World Fab Forecast (WFF)," op.cit.

In contrast to Frontend operations, Backend operations are much less capital intensive, and a higher% of the costs are related to personnel costs. As far back as the 1970's, this led semiconductor companies to move these operations to Asia — where labor costs were significantly lower, and governments were willing to provide significant incentives. Currently, only about 2% of Backend operations are done in the United States, and China and Taiwan account for more than 60% of the world's assembly, packaging, and test capacity.

Trade Liberalization

Given the geographic specialization described above, it is important for semiconductor firms to have companies in other countries as part of their supply chain, and to be able to trade with other countries in as free a manner as possible. In addition, finished semiconductor devices need to be easily shipped to countries where they can be assembled into other products such as electronics and automobiles.

The World Trade Organization's Information Technology Agreement (ITA) — effective since 1997 and further expanded in 2015 — has been instrumental to the strong growth in international trade of semiconductor related products. This agreement has led to integrated circuits being subject to one of the lowest tariffs in international trade. Semiconductors were the world's second most traded product in 2021, ranking only behind crude petroleum and just ahead of refined petroleum.[34]

Mapping the Semiconductor Supply Chain

To say that the semiconductor supply chain is complex is an understatement. As mentioned above, there are four broad steps to semiconductor production: research, design, frontend manufacturing (wafer fabrication), and backend manufacturing (assembly, packaging, and testing). But these broad steps can be broken down into more specific production steps, from making the various chemicals needed to building the wide variety of machines necessary for manufacturing and testing.

The process to build a semiconductor device involves companies from dozens of countries. The process can be so complicated that to create just the wafers on which semiconductor devices are built can take weeks and involve a 1,400-step process.[35] It's been estimated that components for a chip can travel more than 25,000 miles before ever making its way into an electronic device.[36]

Making semiconductors is production intensive, and it can take up to four weeks to grow the ingot from which raw silicon wafers are produced.[37] [38] Creating a new chip can take up to 24 weeks to perfect the design and fabrication process. It can take between 12 and 20 weeks to go through the normal production cycle, and an additional 6 weeks for assembly, packaging, and testing before a chip ever heads out for distribution and installation in an electronic device.[39] Lead time, the time between a new order and delivery, was around 12 weeks in 2019 but reached as high as 25 weeks for some companies during the global pandemic.[40]

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34 Online database, *Observatory of Economic Complexity (OEC)*, https://oec.world/en/profile/world/wld#

35 "Chipmakers Are Ramping Up Production to Address Semiconductor Shortage. Here's Why that Takes Time," *Semiconductor Industry Association*, February 26, 2021, https://www.semiconductors.org/chipmakers-are-ramping-up-production-to-address-semiconductor-shortage-heres-why-that-takes-time/

36 Alam, Syed, et al. "Globality and Complexity of the Semiconductor Ecosystem," op.cit.

37 This doesn't include years that can be spent through the research and development stage.

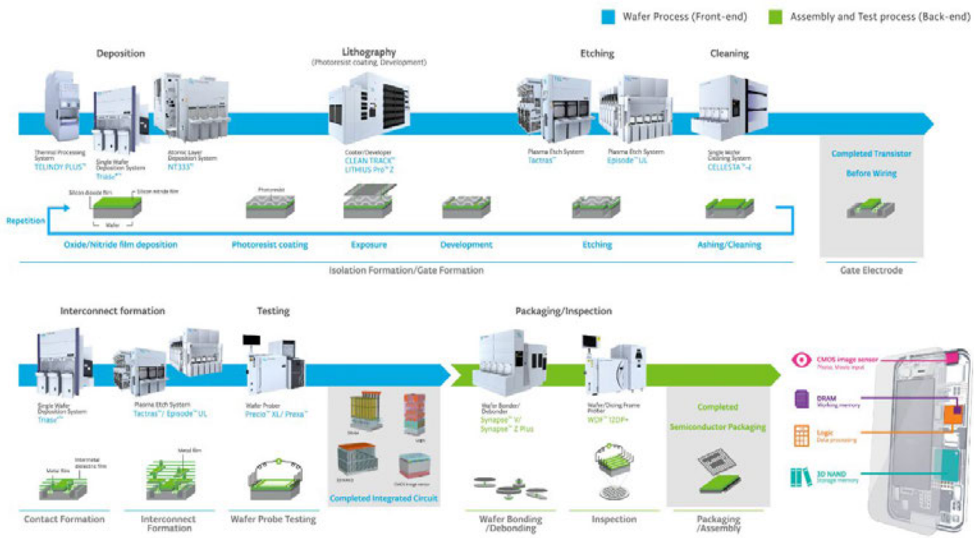
38 "Silicon Wafer Processing | How Are Silicon Wafers Made?," *Wafer World Incorporated*, April 9, 2018, https://www.waferworld.com/post/silicon-wafer-processing-process

39 "Chipmakers Are Ramping Up Production to Address Semiconductor Shortage. Here's Why that Takes Time," op.cit.

40 King, Ian, "Wait Times for Chips Hit Record 18 Weeks as Shortage Deepens," *Bloomberg*, June 22, 2021, https://www.bloomberg.com/news/articles/2021-06-22/wait-times-for-chips-stretch-further-deepening-shortage#xj4y7vzkg

Sometimes inventories can help alleviate changes in demand and take pressure off production lines. The median for chip inventories before the pandemic was 69 days for chips manufacturers, 48 days for distributers, and 50 days for customers.[41] During the global pandemic, however, inventories were less than 5 days for some customers.[42]

Figure 3: Map of the Wafer Fabrication and Assembly & Testing Process



Source - Tokyo Electron Ltd.[43]

As mentioned above, there are generally four semiconductor manufacturing business models for the companies that manufacture chips: Integrated device manufacturers (IDM), foundries, fabless design firms, and outsourced assembly and test companies (OSAT).[44] IDMs generally do all the design, fabrication, assembly and testing in-house. IDMs include Intel Corporation, headquartered in the U.S., and Samsung Electronics headquartered in South Korea. Foundries are essentially fabricators for-hire, usually hired by fabless design firms.

Foundries include Taiwan Semiconductor Manufacturing Company (TSMC) headquartered in Taiwan, and Global Foundries headquartered in the U.S. However, there are also IDMs that have small foundries-for-hire. Intel has announced that it will enter this market with its new fab in Ohio.[45] Finally, an example of an OSAT is ASE Technology, which is headquartered in Taiwan. Between these four business models, a majority of foundries (60%) and OSAT (52%) are operated by Taiwan companies.[46]

[41] Seitz, Patrick, "Chip Inventories At Record Levels, Posing Headwind To Recovery," *Investor's Business Daily*, May 28, 2019, https://www.investors.com/news/technology/chip-inventories-record-levels-posing-headwind-semiconductor-industry/

[42] "Results from Semiconductor Supply Chain Request for Information," *U.S. Department of Commerce*, January 25, 2022, https://www.commerce.gov/news/blog/2022/01/results-semiconductor-supply-chain-request-information

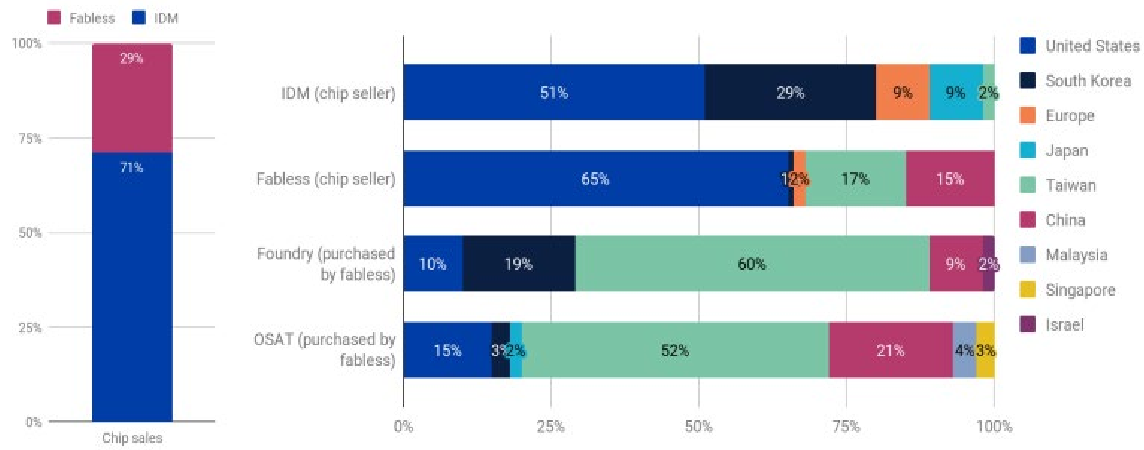
[43] "Manufacturing Process," *Tokyo Electron Ltd.*, https://www.tel.com/product/manufacturing-process/

[44] OSAT also known as Assembly, Testing, and Packaging (ATP). This list doesn't include the wafer, chemical, and machine tool companies that are involved in the manufacturing process.

[45] "Intel Announces Next US Site with Landmark Investment in Ohio," *Intel Newsroom*, January 21, 2022, https://www.intel.com/content/www/us/en/newsroom/news/intel-announces-next-us-site-landmark-investment-ohio.html#gs.xq6wuo

[46] Khan, Saif, Dahlia Peterson, and Alexander Mann, "The Semiconductor Supply Chain: Assessing National Competitiveness," *Center for Security and Emerging Technology*, January, 2021, https://cset.georgetown.edu/publication/the-semiconductor-supply-chain/

Figure 4: The Majority of Foundry and OSAT Market Share is in Taiwan



Source: Center for Security and Emerging Technology[47]

The chips that are manufactured by these various companies are generally split between three kinds of functions: logic chips, memory chips, and discrete, analog, and other (DAO) chips. Global sales of logic chips in 2021 was US$155 billion, representing 28% of total semiconductor sales. Memory chips were US$154 billion, representing just shy of 28% of total sales.[48] And the technology by which these chips are manufactured are often categorized by the size of their smallest features. Currently, the smallest and most advanced chips in production are measured at 3 nanometers (nm). 5 nm and 7 nm chips are also considered leading-edge technology. Memory and DAO chips aren't generally manufactured at the size of the leading-edge logic chips. Indeed, chips as large as a couple hundred nanometers are still being manufactured today.[49]

Chips manufacturing is globally diverse but generally a lot of the high-edge technology is regionally located in East Asia. Taiwan's foundries happen to be the leaders in the production of leading-edge logic chips. Taiwan's share of global logic production is just around 36%, but its share of leading-edge logic chips (7 nm and less) is 74%. 41% of advanced (15 nm) DRAM memory chips also comes from Taiwan.[50] In fact, even a majority of DRAM production by Micron's (an American company) is done in Taiwan.[51]

[47] Ibid.

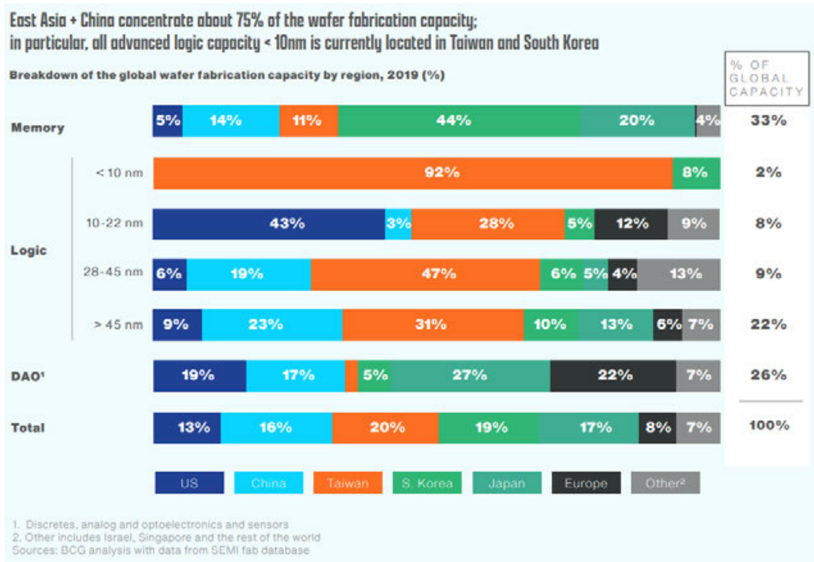
[48] "2022 State of the U.S. Semiconductor Industry," *Semiconductor Industry Association*, November 16, 2022, https://www.semiconductors.org/resources/2022-state-of-the-u-s-semiconductor-industry/

[49] Hunt, Will, "Sustaining U.S. Competitiveness in Semiconductor Manufacturing," *Center for Security and Emerging Technology*, January 2022, https://cset.georgetown.edu/publication/sustaining-u-s-competitiveness-in-semiconductor-manufacturing/

[50] Ibid.

[51] "Micron Technology, Inc, Form 10-K for Fiscal Year Ended September 1, 2022," *Micron Technology, Inc.*, 2022, https://investors.micron.com/static-files/ef9c9309-2e54-4fde-90af-4f10d198650f

Figure 5: Taiwan is the Leader in Logic Fabrication



Source: Boston Consulting Group[52]

While it isn't the most production intensive part of the manufacturing process, the assembly, testing, and packaging is still an essential part of the semiconductor process. Taiwan happens to also be a significant location for OSAT. One of the largest companies for packaging, testing, and electronic manufacturing services, Taiwan-based ASE Technology, did roughly US$21.8 billion revenue in 2022 – 67% of which came from customers located in the U.S.[53]

When thinking about the semiconductor supply chain, it's just as important to consider the devices these chips will go into. That's because what is the value of a chip if it's not being used in a cellphone or computer device? Semiconductors are at the heart of all electronic devices. Our increasingly modern society relies more on electronic devices that can connect, compute, and send information. According to the Semiconductor Industry Association, in 2021 semiconductor sales by their end-use were US$555.9 billion. This is broken down into six broad categories: computers, communications (phones), automotive, consumer electronics, industrial, and government. Personal computers and communications each respectively represent over 30% of total end-use sales.[54]

Logic chips are generally used in the creation of all sorts of data processing electronics. This includes central processing units (CPU) and graphics processing units (GPU), both essential for smartphones and computers. Logic chips are essential for all sorts of industries and sectors like electronics companies, the automotive sector, aerospace, telecommunications, healthcare, data centers, financial services, and defense. What's more is that these industries rely on the continuous supply of these chips. Otherwise, if manufacturers are unable to access chips, it would shut down production lines, or at least force companies to significantly scale back their production.

[52] Varas, Antonio et al., "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era," op.cit

[53] "ASE Technology Holding Co., Ltd. and Subsidiaries Consolidated Financial Statements as of December 31, 2021 and 2022," *ASE Technology Holding Co., Ltd.*, 2022, https://media-aseholdco.todayir.com/20230411124561151143916_en.pdf.

[54] "2022 State of the U.S. Semiconductor Industry," op.cit.

Global Supply Chain Vulnerabilities: Design, Supply, Demand

Gartner, the global research and advisory firm, points out that most supply chain leaders have begun to recognize the need to balance cost and operational efficiency with greater resilience. Gartner has described six strategies for a more resilient supply chain: 1) Inventory and capacity buffers; 2) Manufacturing network diversification; 3) Multisourcing; 4) Nearshoring; 5) Platform, production, or plant harmonization; and 6) Ecosystem partnerships.[55]

President Biden's Executive Order #14017 on America's Supply Chains — issued on February 24, 2021 — stated that the "*United States needs resilient, diverse, and secure supply chains to ensure our economic prosperity and national security. Pandemics and other biological threats, cyber-attacks, climate shocks and extreme weather events, terrorist attacks, geopolitical and economic competition, and other conditions can reduce critical manufacturing capacity and the availability and integrity of critical goods, products, and services.*" President Biden went on to say that "*it is the policy of my Administration to strengthen the resilience of America's supply chains*." [56] A major priority for consideration by the Biden Administration were the semiconductor manufacturing and advanced packaging supply chains.

There are several ways to think about supply chain vulnerabilities and risks. The Supply Chain Operations Reference Model (SCOR) is a management tool used to describe the business processes required to satisfy a customer's demands. The elements of the SCOR model are Plan, Source, Make, Deliver, and Return.[57] At a high level, in the semiconductor supply chain the Plan element includes research and development and product design. The Source element includes the identification and selection of suppliers and raw materials. The Make element includes the production of raw wafers, wafer fabrication, and assembly/testing operations. The Deliver element involves getting finished product to the customer, and the Return element refers to how to dispose of products at the end of life.

There are potential significant sources of disruption within each of these elements, and existing risks for the global semiconductor supply chain as whole can be broadly categorized into Design risks, Supply risks, and Demand risks.

Design Risks

Talent Shortages

The largest risk on the design side of the global semiconductor industry is access to highly skilled talent. Talent shortages may not pose an immediate threat of large-scale disruption for the industry, but it could significantly reduce the industry's long-term ability to maintain its rapid pace of innovation. The industry workforce is aging, with a significant number of current employees in technical positions likely to retire in the next 10-15 years, Furthermore, the industry needs to attract talent with different skill sets, particularly in software development and AI.

In the near term, talent has also become a major concern for the industry. In a 2021 survey of semiconductor industry leaders by KPMG, 30% named talent as one of the top 3 risks threatening their ability to grow over the next three years.[58] This was the third highest risk factor behind territorialism — including cross-border regulation, tariffs, new trade agreements, and national security policies — and supply chain disruptions. In the 2020 version of this survey, talent was tied for the number one risk. The report went on to speculate that the decrease in the 2021 ranking was

55 Hippold, Sarah, "6 Strategies for a More Resilient Supply Chain," *Gartner*, June 23, 2020, https://www.gartner.com/smarterwithgartner/6-strategies-for-a-more-resilient-supply-chain

56 "America's Supply Chains," *Executive Office of the President*, https://www.federalregister.gov/documents/2021/03/01/2021-04280/americas-supply-chains

57 "The SCOR Model for Supply Chain Strategic Decisions," *North Carolina State University*, https://scm.ncsu.edu/scm-articles/article/the-scor-model-for-supply-chain-strategic-decisions

58 "Global Semiconductor Industry Outlook," *KPMG*, February 2021, https://advisory.kpmg.us/content/dam/advisory/en/pdfs/2021/semiconductor-industry-outlook-2021.pdf

likely due to the new work-from-anywhere paradigm. Salary statistics also point to talent supply constraints; wages in the U.S. semiconductor industry have been growing an average of 4.4% since 2001, significantly faster than the growth in wages for the economy as a whole.[59]

Most of the needed talent for the semiconductor industry will come from university undergraduate and graduate programs, with an increasing amount of talent needed in the software development and AI areas. More sophisticated roles will likely be filled by graduate students, who are conducting research with funding grants from the government, research consortia, and directly from industry. Semiconductor-specific workforce programs from states and local governments could also play an important role in driving talent development.

While U.S.-based academic institutions have traditionally provided much of the talent for industry, this is changing. First, many of the Chinese students now choose to go back to China upon graduation. Second, academic institutions in Taiwan, China, Korea, Japan, and Europe now have strong graduate programs that support the industry. While the U.S. also faces challenges regarding talent, the situation is worse for Taiwan. It is estimated that over 3,000 engineers and corporate leaders from Taiwan have accepted employment in China, bringing their talents elsewhere and hollowing-out the talent supply on the island.[60] The lack of competitive wages for young people also contributes to the talent shortage in Taiwan.

Intellectual Property and Trade Secrets

Another major design risk deals with the theft of Intellectual Property (IP) and Trade Secrets (TS). There is a long history of IP and TS theft, with China a common culprit.[61] [62] China has even been known to subsidize Chinese companies in hiring an extensive group of hackers to steal technology, which is then given to other Chinese-subsidized companies to compete in the market. China did this in the clean energy technology space and have even driven U.S. and EU solar and windfarm companies out of business.[63] While China has made some progress on IP related enforcement, challenges persist across several sectors.

One example is the case of the U.S. government versus Fujian Jinhua Integrated Circuit Co., where Fujian Jinhua were accused of economic espionage and conspiracy to steal trade secrets from Micron, with Taiwan company UMC also accused. UMC has pleaded guilty to possessing a Micron trade secret and paid a US$60 million fine. UMC is cooperating with the U.S. government in their case against Fujian Jinhua, which is still under way as of June 2023. An earlier Taiwan case saw Chinese foundry Semiconductor Manufacturing International Corp. (SMIC) accused of industrial espionage and corporate raiding by TSMC, a case that reached settlement and led to substantial reparation payments by SMIC.

The IP problem is particularly relevant to the semiconductor industry because it is cheaper and considerably faster to steal semiconductor IP that it is to reverse engineer existing chips or to develop IP from scratch.[64] Currently, only

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59 "SIA Workforce Roundtable Summary Report," *Semiconductor Industry Association*, March 2018, https://www.semiconductors.org/wp-content/uploads/2018/06/Roundtable_Summary_Report_-_FINAL.pdf

60 Ihara, Kensaku, "Taiwan loses 3,000 chip engineers to 'Made in China 2025'," *Nikkei Asia*, https://asia.nikkei.com/Business/China-tech/Taiwan-loses-3-000-chip-engineers-to-Made-in-China-2025

61 "Top 10 List for Reducing Threat of Semi IP Hacking," *Industrial Automation*, John Blyler, Nov. 19, 2018, https://www.electronicdesign.com/industrial-automation/article/21807309/top-10-list-for-reducing-threat-of-semi-ip-hacking

62 "Findings Of The Investigation into China's Acts, Policies, And Practices Related to Technology Transfer, Intellectual Property, and Innovation Under Section 301 of the Trade Act of 1974," *Office of The United States Trade Representative - Executive Office of the President*, March 22, 2018, https://ustr.gov/sites/default/files/Section%20301%20FINAL.PDF

63 "U.S. Charges Five Chinese Military Hackers for Cyber Espionage Against U.S. Corporations and a Labor Organization for Commercial Advantage," *U.S. Department of Justice*, May 19, 2014, https://www.justice.gov/opa/pr/us-charges-five-chinese-military-hackers-cyber-espionage-against-us-corporations-and-labor

64 "World Awakens to Danger of IP Theft – Again. What's Changed This Time?," *DesignNews*, John Blyler, Oct. 19,2021, https://www.designnews.com/electronics/world-awakens-danger-ip-theft-again-whats-changed-time

TSMC and Samsung are producing IC's at 5 nanometers or less, but China would desperately like to have this capability. Per their most recent 5-year plan, China wants to become a world-class semiconductor technology leader by 2030.

Given that ambition, along with the weak IP and TS enforcement history in China, semiconductor companies must pay attention and take precautions. Theft of IP threatens U.S. leadership in the semiconductor industry and has considerable negative economic effects on the U.S. economy. While the U.S. legal system tries to address these IP issues, litigation is too expensive for all but the largest companies. In addition to the economic consequences, there are also national security risks associated with IP theft, including possibilities such as embedded code that could be used to disable an aircraft's communication during a critical engagement in a combat situation, among others.

In a response to Executive Order 14017, the Semiconductor Industry Association indicates that the future success of the semiconductor industry and the continued American leadership of the industry depends on IP and TS's being protected. [65]

Supply Risks

Perhaps the largest disruption threats to the global semiconductor industry in the short- and medium-terms are the ability to source and transport the numerous resources required to produce semiconductors. These resources include raw silicon wafers; frontend and backend processing equipment; auxiliary resources such as reticles, automated material handling systems, and information technologies to run the business; consumables; and personnel (discussed above).

Natural disasters also pose a considerable risk to semiconductor supply chains. The global pandemic aside, earthquakes, typhoons, tsunamis, droughts, fires, and other natural disasters have impacted different sections of the supply chains in recent years. In response, companies have taken steps to try to mitigate these risks by both diversifying and investing in resiliency.

Silicon Wafers

In 2022, the global demand for silicon wafers for semiconductor applications reached 14.71 billion square inches, up 3.8% from the 14.17 billion square inches that was recorded in the previous year.[66] The raw silicon wafer market includes major Tier 1 and 2 suppliers like Shin-Etsu Chemical Co. (Japan), Ltd., SUMCO Corporation (Japan), GlobalWafers Co.(Taiwan), Siltronic (Germany), and SK Siltron (South Korea). Major wafer manufacturers, such as SUMCO Corporation (Japan) and Hemlock Semiconductor (U.S.), have not invested in new capacity expansion due to the declining prices of silicon wafers, and it has become difficult for manufacturers to maintain or increase profit margins. Also, wafer manufacturers are hesitant to expand silicon manufacturing facilities without prior commitments by chipmakers to fund additional silicon capacity.

Moreover, the global pandemic has added to the challenge faced by wafer manufacturers given the weakening financial situation.[67] Only Shin Etsu Handotai, Sumco, Siltronics, and GlobalWafers Co. have raw silicon manufacturing sites in the U.S. The 300mm production from these facilities does not meet current domestic needs, and the situation will only get worse with Intel's expansion and the future demand from new U.S.-based TSMC and Samsung facilities.

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[65] "Response to Executive Order 14017," Semiconductor Industry Association, April 5, 2021, https://www.semiconductors.org/wp-content/uploads/2021/04/4.5.21-SIA-supply-chain-submission.pdf

[66] "Silicon Shipment Statistics," *SEMI*, https://www.semi.org/en/products-services/market-data/materials/si-shipment-statistics

[67] "Thin Wafer Market with COVID-19 impact analysis by Wafer Size (125 mm, 200 mm, and 300 mm), Process (Temporary Bonding & Debonding and Carrier-less/Taiko Process), Technology , Application, and Geography - Global Forecast to 2025," *marketsandmarkets.com*, "https://www.marketsandmarkets.com/Market-Reports/thin-wafer-market-255706993.html

An example of the potential impact of silicon wafer shortages is the 2011 major earthquake that struck Japan, followed by a tsunami and nuclear power-plant meltdown. 25% of the global production of silicon wafers and 75% of the global supply of hydrogen peroxide were affected by the disaster. Several fabs were shut down for several months.

Processing Equipment

Semiconductor manufacturing uses more than 50 different types of sophisticated wafer processing and testing equipment provided by specialist vendors for each step in the fabrication process. Fortunately, U.S. firms have a greater than 50% market share in most semiconductor manufacturing categories. Two notable exceptions are that Japan has a greater than 90% share of the critical photoresist processing market, and ASML, a Dutch company, currently produces the only EUV machines that are necessary for producing integrated circuits at 7 nm and below.

EUV machines are very expensive (US$150 million and way up from there) and given that there is only a single supplier, their availability is a key vulnerability in the leading-edge semiconductor supply chain. We note that any disruptions to a critical supplier to ASML (e.g. ZEISS, a German company that supplies the lenses used in ASML's EUV machines) will also cause a disruption for all leading-edge semiconductor production.

According to industry group SEMI, the global Semiconductor Manufacturing Equipment market was US$$107.6 billion in 2022 - an industry record, growing 6% year on year.[68] The EUV market is expected to increase from US$ 11.49 billion in 2023 to US$ 20.18 billion by 2028, at a CAGR of 11.93 % during the forecast period.[69]

Materials

There are as many as 300 different materials needed to produce an advanced semiconductor, with many of them very sophisticated and specialized for the semiconductor industry. For example, the polysilicon employed to make the silicon ingot that is subsequently sliced into wafers is required to have a purity level that is 1,000 times higher than the level required for solar energy panels.

This type of polysilicon is primarily produced by just four companies, which have a combined global market share above 90%. Frontend materials include polysilicon, silicon wafers, photo masks, photoresist, wet processing chemicals, gases, and Chemical Mechanical Planarization slurries. Backend materials include leadframes, organic substrates, encapsulation resins, bonding wires, and die-attach materials.

The global semiconductor materials market reached US$72.7 billion in revenue in 2022, surpassing the previous market high of US$66.8 billion set in 2021. Asia accounted for roughly 73% of the 2022 materials market, with Taiwan the number one consumer for the 13th year in a row, at US$20.1 billion, due to its extensive foundry and packaging business.[70]

The impact of an explosion of a Sumitomo Chemical factory in Japan in 1993 is often cited to illustrate the magnitude of the risk to the semiconductor materials market. The explosion impacted 60% of the global supply of epoxy resin, and spot prices for DRAM memory chips in the U.S. market spiked from an average of US$30/megabyte to around

68 "Global Semiconductor Equipment Billings Reach Industry Record US$107.6 Billion In 2022, SEMI Reports," *SEMI*, April 12, 2023, https://www.semi.org/en/news-media-press-releases/semi-press-releases/global-semiconductor-equipment-billings-reach-industry-record-%24107.6-billion-in-2022-semi-reports

69 "Extreme Ultraviolet Lithography Market Size & Share Analysis - Growth Trends & Forecasts (2023 - 2028)," Mordor Intelligence, 2023, https://www.mordorintelligence.com/industry-reports/extreme-ultraviolet-lithography-market

70 "Global Semiconductor Materials Market Revenue Reaches Record US$73 Billion in 2022, SEMI Reports," *CISION PR Newswire*, June 13, 2023, https://www.prnewswire.com/news-releases/global-semiconductor-materials-market-revenue-reaches-record-73-billion-in-2022-semi-reports-301847676.html

US$80/megabyte.

Another example is that in 2019, geopolitical tensions saw Japan imposing export controls on certain semiconductor materials and restricting their export to South Korea. The impact on the South Korean semiconductor industry was significant, given that Japan was a major or leading supplier of those materials. An estimate by the Office of the U.S. Trade Representative (USTR) calculated that up to US$7.7 billion per month in semiconductor exports from South Korea could be affected by Japan's export restrictions.[71]

The war in Ukraine is another very recent example of the potential impact of a geopolitical conflict on the semiconductor materials industry. Neon is a major component in the manufacturing of semiconductors, and Ukraine and Russia supplied 40-50% of the global supply of neon prior to the Russian invasion of Ukraine. Roughly 250 tons of neon were produced annually by just two Ukrainian companies.[72] Production in Ukraine is not expected to restart anytime soon, and prices of these materials have spiked. Semiconductor companies have had to make adjustments that include reducing usage, developing additional supplies and suppliers, coordinate among different suppliers, and increasing recycling.[73]

Water and Power

Marie Garcia Bardon – a senior researcher at the Imec nanotechnology center in Belgium, who does pioneering work estimating aspects of the industry's carbon footprint – stated that "t*he general trend is the energy consumption is increasing, the water consumption is increasing as all chips become more and more complex*."[74] Stable access to water and power are therefore likely to continue to be a part of the calculus for semiconductor companies around the globe.

Water is fundamental to manufacturing semiconductors. Over a series of steps, semiconductors are built in layers on silicon wafers into integrated circuits (chips). After each one of several dozen layers of semiconductors are added to the silicon wafer, the wafer must be rinsed — requiring massive amounts of water. A great deal of this water needs to be Ultra Pure Water (UPW), which is thousands of times purer than drinking water. To make 1,000 gallons of UPW takes roughly 1,400 -1,600 gallons of municipal water.[75]

To create an integrated circuit on a 300mm/12-inch wafer requires 2,200 gallons of water as a low-end estimate, including 1,500 gallons of UPW.[76] For a fab that produces 20,000 wafers per month, that equates to at least 1.47 million gallons per day (MGD). However, TSMC estimates that the new plant in Arizona, which plans for 20,000 wafer starts per month (WSPM), will utilize 13.6 MGD. While 65% of that will be recycled, the fab will still need an average of 4.75 MGD of fresh water.

Semiconductor companies have responded to concerns over water access by increasing their recycling — using their water intake for more than one purpose and using each drop of water more than once. New fabs are being built with an

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71 "The South Korea-Japan Trade Dispute in Context: Semiconductor Manufacturing, Chemicals, and Concentrated Supply Chains," *Office of the U.S. Trade Representative*, Working Paper ID-062, October 2019, https://usitc.gov/publications/332/working_papers/the_south_korea-japan_trade_dispute_in_context_semiconductor_manufacturing_chemicals_and_concentrated_supply_chains.pdf

72 "The war in the Ukraine is anticipated to have an impact on car prices", *mytwintiers.com*, https://www.mytwintiers.com/automotive/neon-shortage-sparks-second-wave-of-chip-shortages

73 "TSMC to secure neon in Taiwan after Ukraine shock for chip sector," *Nikkei Asia*, November 10, 2022, https://asia.nikkei.com/Business/Tech/Semiconductors/TSMC-to-secure-neon-in-Taiwan-after-Ukraine-shock-for-chip-sector

74 "The Chip Industry Has a Problem With Its Giant Carbon Footprint," *Supply Chain Brain*, April 9, 2021, https://www.supplychainbrain.com/articles/32910-the-chip-industry-has-a-problem-with-its-giant-carbon-footprint

75 "8 Things You Should Know About Water & Semiconductors," *China Water Risk, https://www.chinawaterrisk.org/resources/analysis-reviews/8-things-you-should-know-about-water-and-semiconductors/*

76 "Pure water, semiconductors and the recession," *Global Water Intelligence*, Vol 10, Issue 10 (October 2009), https://www.globalwaterintel.com/global-water-intelligence-magazine/10/10/uncategorized/pure-water-semiconductors-and-the-recession

eye to water conservation efforts, and to implementing sustainable water resource management strategies.[77] While the recycling of water has reduced the potential impact of water shortages, manufacturing semiconductors is clearly still highly water intensive and still requires some access to fresh water.

A recent example of the key role of water for the industry is the significant Taiwan drought in 2021. Taiwan reduced water supplies to several areas — including to a key hub of semiconductor manufacturing in the central part of the island — to stop reserves from running dry.[78] Fortunately the semiconductor companies located there were able to avoid any significant loss of production during this time, although some had to resort to trucking in water from elsewhere. Climate model projections have placed Taiwan in the risk zone for droughts in the future, which could mean a greater risk for additional water issues.[79]

A stable energy supply is also a concern for semiconductor companies. An estimate from 2013 suggests that a single fab can use up to 30-50 megawatts of peak electrical capacity, enough to power a small city.[80] The power needed for a new fab in 2023 is surely greater than that, due to the increased complexity of leading-edge semiconductor manufacturing. These increased power needs have led some municipalities to invest in additional electrical power to support the development of a new fab.[81]

One example of the importance of energy supply to the industry was the devastating September 1999 Taiwan earthquake that caused a six-day shutdown of the Hsinchu Science Park due to power outages. As a result, memory-chip prices tripled and shares of electronics companies around the world tanked, with IBM, Hewlett Packard, Intel, and Xerox — all part of the Fortune 100 at the time — losing 18-40% of their value in the month after the earthquake.

Other examples include when a severe ice storm in Texas in February 2022 caused widespread power outages and caused NXP, Samsung, and Infineon fabs to go offline, and when a December 2020 a power outage affected a memory fab located in Taiwan for just one hour - taking it offline for several days for restarts and causing some output to be scrapped. This one fab by itself normally produces 8.8% of the global DRAM supply, and the supply uncertainty caused DRAM spot prices to spike.[82]

Taiwan is susceptible to issues surrounding energy supply. There are other locations, like the United States, where access to stable power is less of a concern.

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77 Barrett, Eamon, "Taiwan's drought is exposing just how much water chipmakers like TSMC use (and reuse)," *Fortune*, June 12, 2021, https://fortune.com/2021/06/12/chip-shortage-taiwan-drought-tsmc-water-usage/

78 "Taiwan Cuts Water Supply for Chipmakers as Drought Threatens to Dry Up Reserves," *Bloomberg.com*, March 24, 2021, https://www.bloomberg.com/news/articles/2021-03-24/taiwan-raises-red-alert-over-water-cuts-supply-for-chipmakers

79 "Taiwan may face fewer typhoons - but harsher drought - as planet warms," *Reuters*, December 21, 2020, https://www.reuters.com/article/us-climate-change-taiwan-typhoon-feature/taiwan-may-face-fewer-typhoons-but-harsher-drought-as-planet-warms-idUSKBN28W00D

80 "8 Things You Should Know About Water & Semiconductors," op.cit.

81 "Chandler commits US$14 million to power Intel expansion," *San Tan Sun News,* July 22,2021, https://santansun.com/2021/07/22/chandler-commits-14-million-to-power-intel-expansion/

82 Shilov, Anton, "Micron's Fab Goes Offline for One Hour, DRAM Prices Go Up," *Tom's Hardware*, December 3, 2020, https://www.tomshardware.com/news/micron-fab11-outage

Demand Risks

The semiconductor supply chain can also be disrupted by changes in demand for semiconductors. This can be an increase, a decrease, or simply a shift in demand for different types of computer chips. Because of the *bullwhip effect*, even a small change in demand for end-use products can cause significant variability and disruptions further upstream in the supply chain.[83] Thus, changes in demand for items such as automobiles, computers, and other electronic devices can have an outsized negative impact on stability and availability in the semiconductor supply chain.

Such demand changes can be due to regular business cycles, due to geopolitical issues such as trade barriers or military conflicts, as well as due to manmade and natural disasters. All three types of changes in demand have affected the semiconductor supply chain during the COVID-19 pandemic and will be discussed in detail below.

[83] "Information distortion in a supply chain: The bullwhip effect". Lee, H.; Padmanabhan, V.; Whang, S., *Management Science*. 43 Vol 4, pp. 546–558, 2007. doi:10.1287/mnsc.43.4.546

Taiwan's Importance and Role in the Global Technology Supply Chain

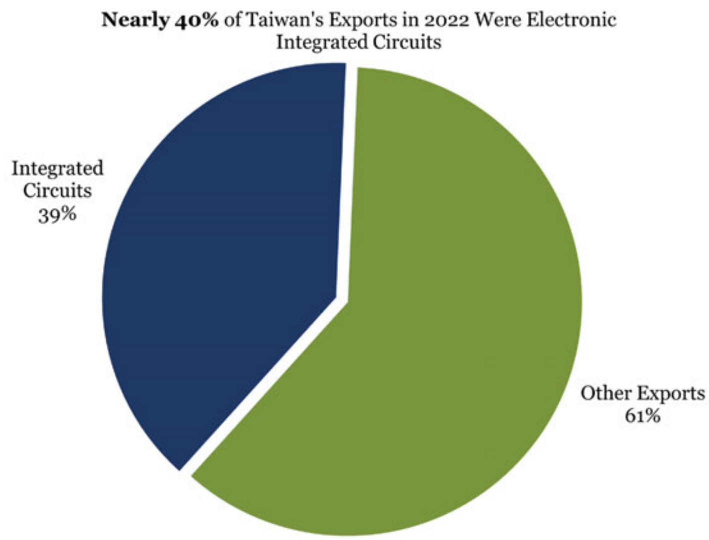
Today, Taiwan is unquestionably one of the global leaders in the semiconductor industry, especially in manufacturing where it has become a major hub for cutting-edge semiconductor production. As it has grown in importance, Taiwan has also been a beneficiary of foreign investment in its semiconductor sector. Several U.S. companies maintain extensive investments on the island, including Micron Technology — a major and long-term investor that has acquired and operates several memory fabs there – and Diodes, Inc., and there have also been recent expanded investments from U.S. companies such as Qualcomm and semiconductor material producer Entegris.

The value of Taiwan's semiconductor industry to the global economy is nearly immeasurable. This is because it's hard to measure not just the total value of research, design, and capital investment that has been created over the last several decades by Taiwan companies. There is also an immeasurable amount of knowledge and talent built on the island that puts Taiwan in the position as a global leader.

Snapshot: The Global Semiconductor Economy

As we look at Taiwan's semiconductor industry based on today's values, in 2022 integrated circuits accounted for nearly 40% of Taiwan's total exports. They are Taiwan's number one export, and this value is the equivalent of nearly a quarter of Taiwan's Gross Domestic Product (GDP).

Figure 6: IC's Are Taiwan's Number One Export

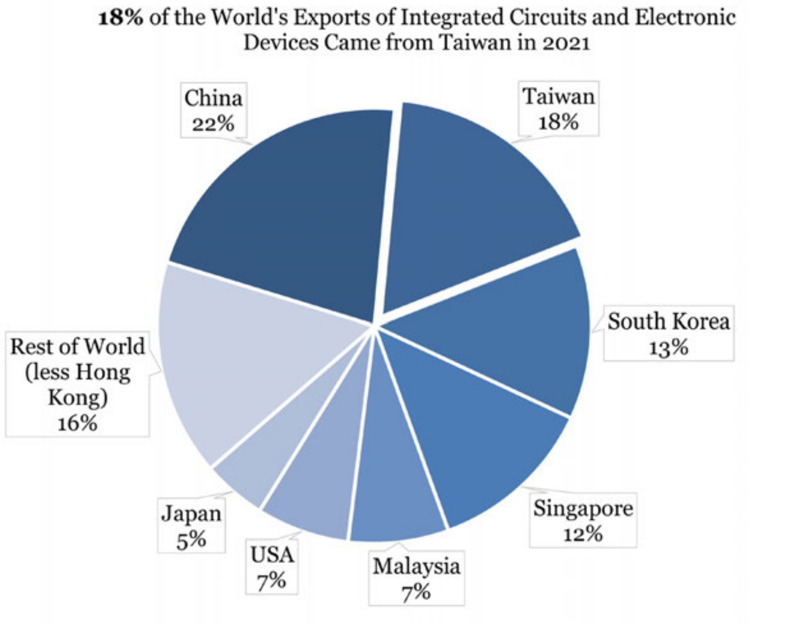


Source: Bureau of Foreign Trade, Ministry of Economic Affairs, Taiwan[84]

It's not just Taiwan that exports semiconductors. Global economies exported (and re-exported) over US$1 trillion worth of integrated circuits and electronic components in 2021. 18% of the world's exports of integrated circuits and electronic devices are from Taiwan. ICs from Asia makes up more than half of the world's supply, with 22% coming from China and 13% coming from South Korea. A significant percentage also comes from Hong Kong.

[84] Trade Statistics, The Bureau of Foreign Trade, *Ministry of Economic Affairs, Taiwan*, https://cuswebo.trade.gov.tw/FSCE020F/FSCE020F

Figure 7: Global Exports of ICs and Electronic Devices



Source: World Trade Organization[85]

The global trade of any product, especially one as globally diverse as semiconductors, is more complicated than what's often captured by trade statistics. National trade accounts generally only capture the bilateral import and export of goods between two trading partners. According to Taiwan's national statistics, more than half of the US$173.5 billion worth of chips Taiwan exported in 2022 went to China and Hong Kong. Meanwhile, only 2% of IC exports went directly to the U.S. However, much of what went to China and Hong Kong ends up in electronic products for the U.S. market.

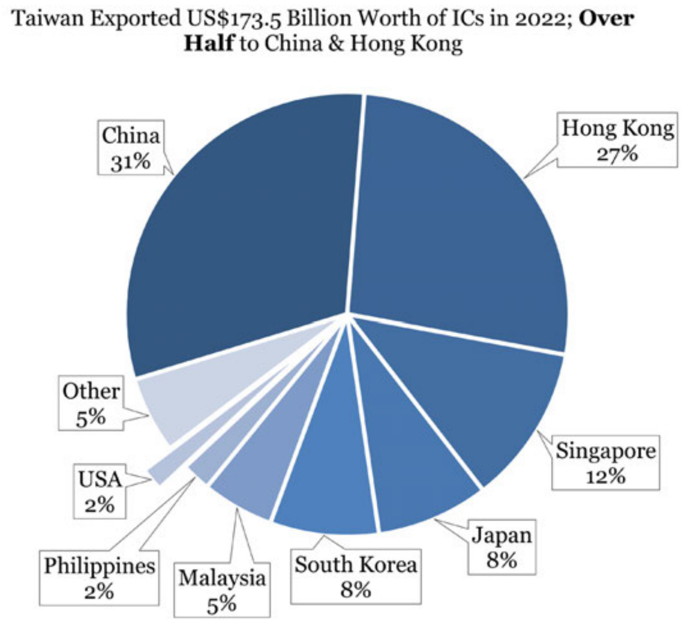
It's hard for national accounts to capture the flow of goods across multiple economies. For example, 27% of Taiwan's IC exports went to Hong Kong in 2022, and Hong Kong is in fact the world's largest IC exporter by value. However, most exports out of Hong Kong are re-exports, meaning these were goods produced in other countries that simply flow through Hong Kong's port.[86]

Hong Kong's two largest trading partners for ICs are China and Taiwan. While 81% of Hong Kong's exports of ICs goes to China, only 4% goes to Taiwan. Additionally, 37% of Hong Kong's imports of ICs comes from Taiwan while only 23% comes from China. This further shows that Taiwan exports a lot more of its ICs to China if you add reexports through Hong Kong, figures that are not captured by general trade statistics.

[85] WTO Stats, *WTO*, https://stats.wto.org/

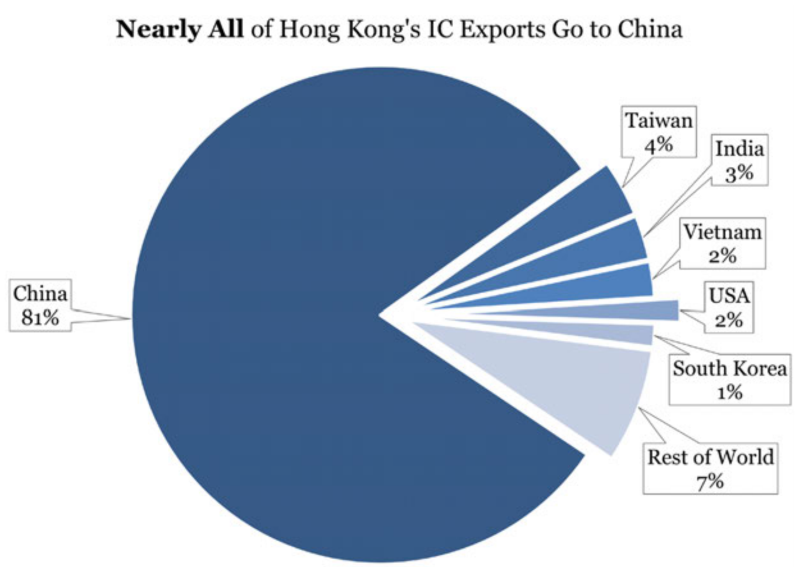
[86] "Hong Kong's Values of Re-exports by Main Origin, 2022," Trade and Industry Department, *The Government of the Hong Kong Special Administration Region*, 2022, https://www.tid.gov.hk/english/aboutus/publications/tradestat/rxori_text.html

Figure 8: 58% of Taiwan's 2022 IC Exports Went to China & Hong Kong



Source: Taiwan Bureau of Foreign Trade

Figure 9: Nearly All Hong Kong's IC Exports Go to China



Source: Interactive Data Dissemination Service for Trade Statistics, Census and Statistics Department, Government of Hong Kong[87]

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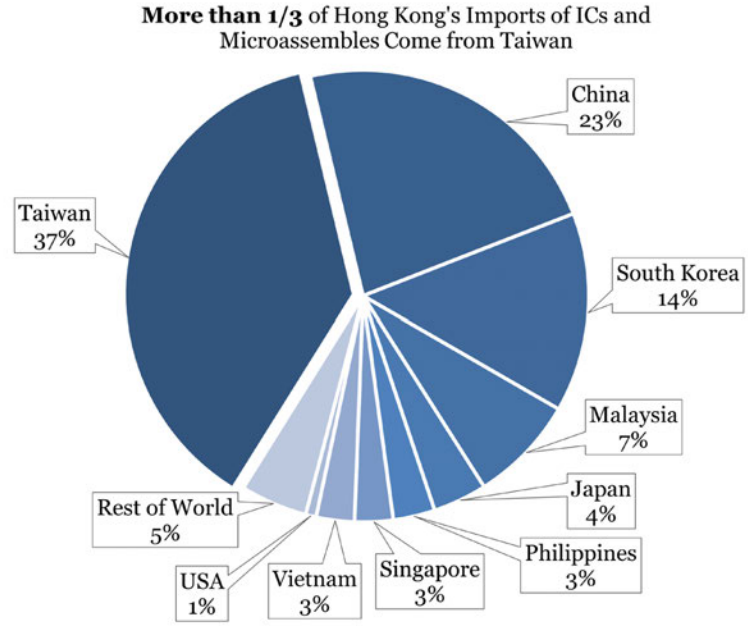
[87] Interactive Data Dissemination Service for Trade Statistics, Census and Statistics Department, *Government of Hong Kong*, https://tradeidds.censtatd.gov.hk/

Figure 10: Hong Kong Imports of ICs and Microassembles

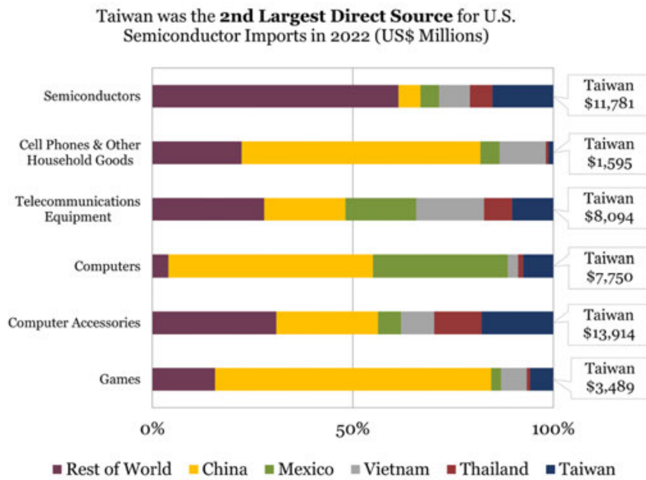


Source: Interactive Data Dissemination Service for Trade Statistics, Census and Statistics Department, Government of Hong Kong

Snapshot: The U.S.-Taiwan Economic Relationship

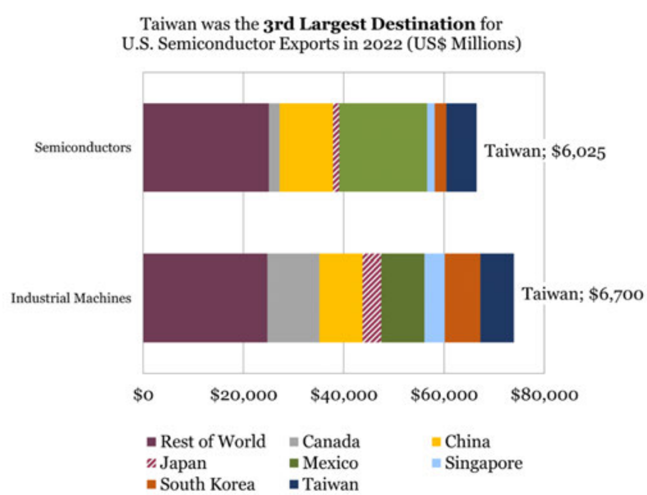
The U.S. and Taiwan have a rich history of trading goods and services. In 2022, Taiwan was America's 9th largest trading partner. The U.S. exported US$43.7 billion worth of goods to Taiwan, and imported US$91.8 billion worth of goods, for a combined total trade in goods worth US$135.6 billion.[88] Trade in semiconductors made up a large portion of this. Taiwan is the second largest source of U.S. semiconductor imports, with nearly US$12 billion worth of imports in 2022.[89] The U.S. exported just over US$6 billion worth of semiconductors to Taiwan during the same period.

Figure 11: U.S. Semiconductor & Technology Imports in 2022



Source: *Country and Product Trade Data by End-Use, U.S. Census Bureau*[90]

Figure 12: Taiwan as a Destination for U.S. Semiconductor Exports



Source: Country and Product Trade Data by End-Use, U.S. Census Bureau

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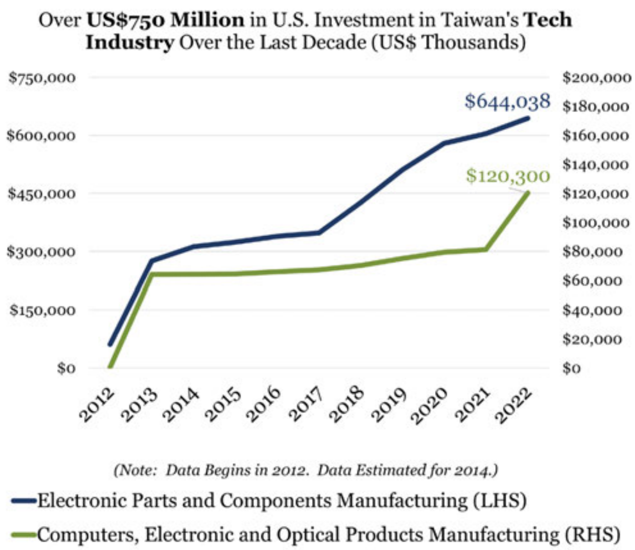
88 "Trade in Goods with Taiwan," *U.S. Census Bureau*, https://www.census.gov/foreign-trade/balance/c5830.html

89 Malaysia just happened to be the number one source of semiconductor imports by value into the U.S. in 2022, with an annual value of US$18.9 billion.

90 Country and Product Trade Data by End-Use, *U.S. Census Bureau*, https://www.census.gov/foreign-trade/index.html

There is also a rich history of investment between the U.S. and Taiwan. In the last decade, over US$750 billion worth of American investment has gone into Taiwan's computer and electronics manufacturing capabilities – this includes semiconductor production. Taiwan investment in America has generally been positive too but has exploded in the last few years with the announcement of TSMC's investment in Arizona. This has sparked a wave for new investments from Taiwan-based companies in the U.S. that are a part of the semiconductor supply chain.[91] Examples include GlobalWafer's investment in Texas, along with investments in Arizona by Sunlit Chemical, KPPC Chemicals, and Chang Chun.[92]

Figure 13: U.S. Investment in Taiwan's Tech Industry



Source: Investment Commission, Ministry of Economic Affairs, Taiwan[93]

The U.S.-Taiwan semiconductor industry relationship is a perfect example of "comparative advantage." Taiwan manufacturers are invested in advancing their manufacturing processes, while American companies have benefited by outsourcing manufacturing of their products to these Taiwan companies as they invest more in R&D and development.

The fabless-foundry business model has also given Taiwan companies the opportunity to advance their design capabilities. Some American companies rely on Taiwan for their final products, with examples being Cisco's use of MediaTek technology and Dell's use of Himax. According to one estimate, "*more than 23,100 U.S. companies buy directly from Taiwan suppliers at tier-1, while more than 112,500 buy indirectly at tier-2, and over 237,500 at tier-3.*"[94]

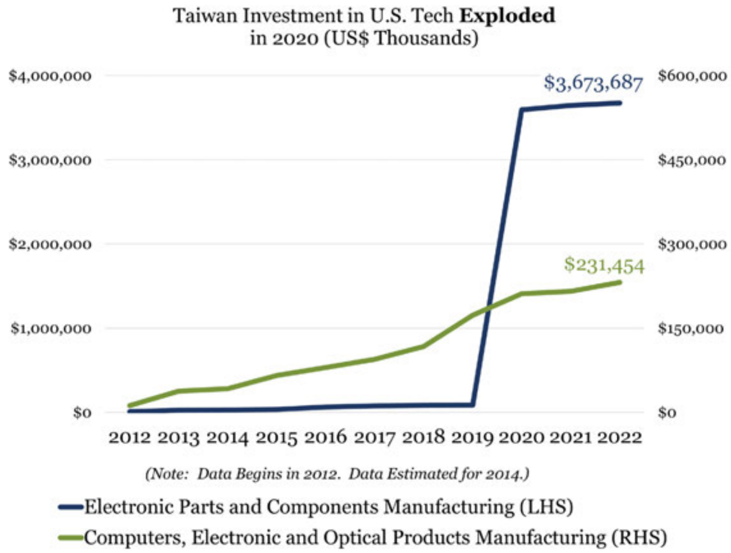
[91] "U.S. Semiconductor Ecosystem Map," *Semiconductor Industry Association*, April 17, 2023, https://www.semiconductors.org/u-s-semiconductor-ecosystem-map/

[92] "Taiwan's GlobalWafers to Invest US$5 Billion in New Silicon Wafer Plant in Texas," *Reuters*, June 27, 2022, https://www.usnews.com/news/technology/articles/2022-06-27/taiwans-globalwafers-to-invest-5-billion-in-new-silicon-wafer-plant-in-texas, Marinescu, Adriana, "$100M Phoenix Plant Breaks Ground," *Commercial Property Executive*, January 21, 2022, https://www.commercialsearch.com/news/semiconductor-industry-supplier-breaks-ground-on-100m-facility/, "KPCT to Build Semiconductor Chemical Manufacturing Facility in Casa Grande," *Arizona Commerce Authority*, November 22, 2022, https://www.azcommerce.com/news-events/news/2022/11/kpct-to-build-semiconductor-chemical-manufacturing-facility-in-casa-grande/, and "Chang Chun Arizona Breaks Ground on Manufacturing Facility in Casa Grande," *Arizona Commerce Authority*, October 20, 2022, https://www.azcommerce.com/news-events/news/2022/10/chang-chun-arizona-breaks-ground-on-manufacturing-facility-in-casa-grande/

[93] Investment Commission, *Ministry of Economic Affairs*, https://www.moeaic.gov.tw

[94] John, Geraint, "Why Taiwan Could Be the Next Source of Global Supply Chain Disruption," *Interos*, April 11, 2022, https://www.interos.ai/blog-why-taiwan-could-be-the-next-source-of-global-supply-chain-disruption/

Figure 14: Taiwan Investment in the U.S. Tech Industry



Source: Investment Commission, Ministry of Economic Affairs, Taiwan

Snapshot: Taiwan's Global Position

Taiwan was the second-largest global destination for semiconductor equipment spending in 2022 at US$26.8 billion, an increase of 8% over the previous year, and marking a fourth straight year of growth.[95] Taiwan has maintained its high equipment spending as local firms expand production capacity and upgrade their technologies. Due to the long lead times for semiconductor equipment, this positions Taiwan well to lead on semiconductor production for the next few years.

The success of TSMC and of their domestic competitors has helped boost Taiwan's global market share in the increasingly competitive foundry segment. Market share for companies from Taiwan – which includes TSMC, UMC, Powerchip Technology Corporation, and Vanguard International Semiconductor Corporation — was estimated at 68.7% in Q1, 2023, climbing from its 2021 and 2022 market share figures but still well below its historical highs. According to TrendForce, this rise in market share for Taiwan comes among the significant decline in foundry revenue in early 2023 due to sustained weak end-market demand that is intensifying a decline during the off-peak season. The foundry revenue decline is expected to continue into 2023.[96]

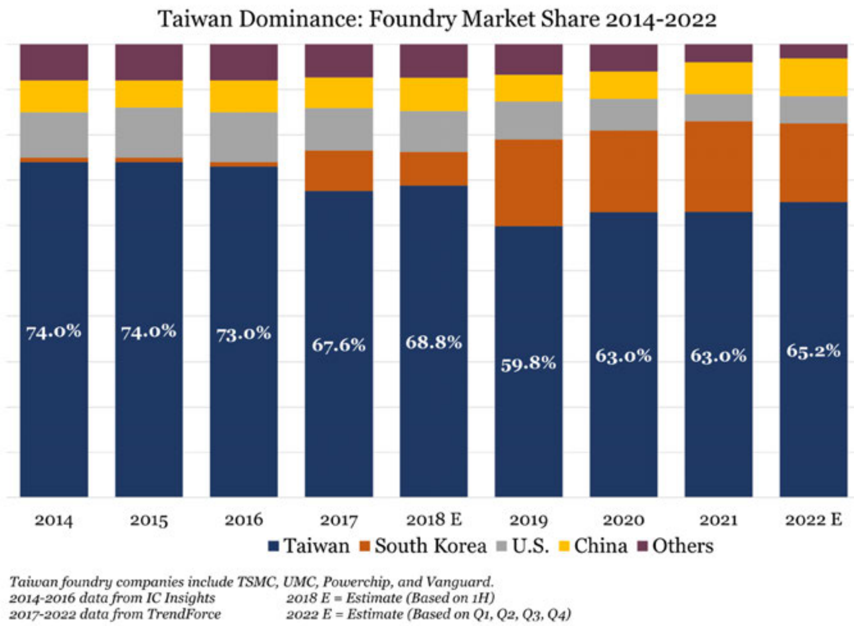
While Taiwan's foundry industry market share has been predicted to fall to as low as 44% in 2026 - as the U.S., China, and others attempt to develop their domestic capacity to increase chip supply chain resilience due to rising geopolitical concerns – Taiwan should remain the largest player in the foundry space for the foreseeable future.[97]

[95] "Global Semiconductor Equipment Billings Reach Industry Record US$107.6 Billion In 2022, SEMI Reports," op.cit.

[96] "Top 10 Foundries Report Nearly 20% QoQ Revenue Decline in 1Q23, Continued Slide Expected in Q2, Says TrendForce," *TrendForce*, June 12, 2023, https://www.trendforce.com/presscenter/news/20230612-11719.html

[97] "Taiwan's foundry global share to dip: TrendForce," *Taipei Times*, May 26, 2023, https://www.taipeitimes.com/News/biz/archives/2023/05/26/2003800439

Figure 15: Taiwan Dominance — Foundry Market Share 2014-2022



Source: 2014-2016 data from IC Insights, 2017-2022 data from TrendForce

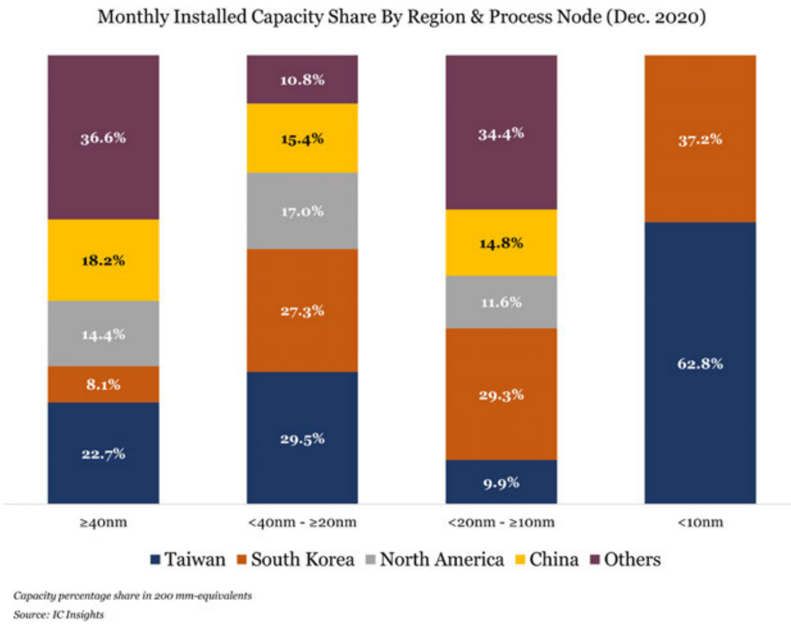
Taiwan also holds a substantial share of overall global IC industry capacity. In particular at the less than 10 nm process node, the island holds by far the largest share of manufacturing capacity for any country in the world, with South Korea (through Samsung) trailing in this category.[98] See the below figure for the percentage share of total monthly installed capacity, in 200 mm-equivalents, by geographic region and by process node, as of December 2020 (the most recent period for which this specific data is available).

TSMC continues to push towards utilization of its 3 nm node process, while competing semiconductor foundries are doing their best not to fall behind. For example, Samsung recently announced that it would be unveiling its new 3 nm and 4 nm processes in June of 2023.[99]

[98] "Semiconductor Wafer Installed Capacity Per Process Node," *AnySilicon*, October 14, 2021, https://anysilicon.com/semiconductor-wafer-installed-capacity-per-process-node/

[99] "Samsung To Officially Unveil Its 3nm, 4nm Technologies In June, With Up To 34 Percent Power Efficiency Improvements," WCCF Tech, Inc., May 22, 2023, https://wccftech.com/samsung-unveiling-3nm-4nm-technologies-in-june

Figure 16: Monthly Installed Capacity Share by Region & Process Node



Source: IC Insights

Finally, as we discussed above, Taiwan is also a leader when it comes to semiconductor assembly and testing. This market segment consists of companies that provide packaging for devices made by foundries, and/or that test devices prior to shipping. Six of the top 10 Outsourced Assembly and Test Companies (OSATs) by revenue are Taiwan companies, and in 2021 they accounted for 52% of the OSAT market.[100]

Snapshot: TSMC

TSMC is perhaps one of the most well-known semiconductor companies outside of Taiwan. Besides Samsung, TSMC is the only other company in the world that currently holds leading-edge technology manufacturing capacity at scale. It is also one of the world's largest semiconductor manufacturers. TSMC uses a wide range of technologies — from old-school 2 microns to state-of-the-art 3 nm – and leads on development of future technologies.[101] Almost all of the leading U.S.-headquartered fabless companies (e.g. Broadcom, Qualcomm, NVIDIA, AMD, Apple, Xilinx, etc.) heavily utilize TSMC's foundry services.

The U.S. government recognizes the importance of TSMC to the semiconductor industry. In January 2020, the United States government urged TSMC to begin producing leading-edge chips in the U.S. to ensure a supply of high-security components manufactured on U.S. soil.[102] The U.S. apparently hoped to get access to domestically produced chips for the defense sector, among others, although the relatively small volume of chips used in the defense industry did not by itself provide a compelling business case for moving production to the U.S.[103]

[100] Khan, Saif, et al., "The Semiconductor Supply Chain: Assessing National Competitiveness," op.cit. and "Revenue of leading outsourced semiconductor assembly and test (OSAT) companies from 2019 to 2021, by quarter," *statista.com*, https://www.statista.com/statistics/1120619/x/

[101] "About TSMC," *TSMC*, https://www.tsmc.com/english/aboutTSMC

[102] Li, Lauly and Ting-Fang Cheng, "Exclusive: Washington pressures TSMC to make chips in US," *Nikkei Asian Review*, January 15, 2020, https://asia.nikkei.com/Business/Technology/Exclusive-Washington-pressures-TSMC-to-make-chips-in-US

[103] Liao, Holmes, "The US is increasingly concerned about risks to TSMC's supply chain," *Taiwan News*, January 3, 2020, https://www.taiwannews.com.tw/en/news/3883441

In May of 2020, TSMC made an unprecedented announcement; they would make a major investment in their manufacturing operations and build a new, high-end fab in the United States. TSMC announced that the new fab would be deployed in Arizona, would have the ability to handle more than 20,000 wafers a month, and that it would utilize the company's 5 nm process. When first announced, the price tag for this fab was approximately US$12 billion. In December 2022, TSMC announced that it would triple its planned investment in Arizona to US$40 billion, making it among the largest foreign investments in U.S. history and TSMC's largest investment outside Taiwan. They also announced that they were planning for two fabs in Arizona, with the second using TSMC's cutting-edge 3 nm process. Construction on the first fab started in 2021, and it is scheduled to start production in 2024. The second fab is expected to begin production in 2026.[104]

The TSMC Arizona fabs will be some of the most technically advanced facilities in the country. The new fabs will create approximately 4,500 local jobs from TSMC alone, with another 8,500 high-tech jobs created by associated suppliers, and it will be a boon to the semiconductor industry ecosystem in Arizona.[105] This is particularly true as the TSMC investment has already drawn several additional suppliers of chemicals and other semiconductor-related goods and services to the area in a clustering effect. Sunlit Chemical, a leading Taiwan chemical supplier to the semiconductor industry, has already broken ground on a new manufacturing facility in the Phoenix area.[106] While this investment represents a small percentage of TSMC's overall global footprint, with the company's primary operations still in Taiwan, this is a good first step.

The 2020 TSMC announcement was just the first of several new semiconductor manufacturing investments in the United States. In 2021, Intel announced that it would spend US$20 billion to build two new plants also in Arizona, and Samsung announced a US$17 billion investment – it's largest ever in the U.S. – in Texas. In 2022, Intel announced an initial investment of more than US$20 billion to construct two new leading-edge chip factories in Ohio that will provide foundry services.

The semiconductor industries on both sides of the Taiwan Strait are intertwined, and Taiwan companies have also been reliant on demand from China. For example, TSMC's exports to China had been substantial prior to 2020, with Chinese company Huawei serving as the company's second-biggest customer.[107] Due to U.S. sanctions announced in May 2020, however, TSMC had to adjust. Orders from other major clients appear to have made up for the loss of revenue due to the U.S. restrictions.[108] In fact, the company's total revenue in 2022 grew 42.6% year-on-year.[109]

While TSMC is not the only Taiwan company with a global presence, a snapshot of TSMC's capacity gives us an idea of what would be lost if Taiwan-made chips were no longer accessible.

Over the last 15 years, TSMC alone has invested US$163 billion in its capital expenditure, and TSMC Capex since 2009 has been growing exponentially. These investments have allowed for continued advancements in its manufacturing process, from producing at 40/45 nm in 2009 to 5 nm sales starting just a few years ago. TSMC announced at the end

[104] "TSMC triples Arizona chip plant investment, Biden hails project," *Reuters*, December 7, 2022, https://www.reuters.com/technology/biden-visit-taiwans-tsmc-chip-plant-arizona-hail-supply-chain-fixes-2022-12-06/

[105] Ibid.

[106] Arizona Commerce Authority, "Sunlit Breaks Ground on Phoenix Facility," *SignalsAZ.com*, January 23, 2022, https://www.signalsaz.com/articles/sunlit-breaks-ground-on-phoenix-facility/

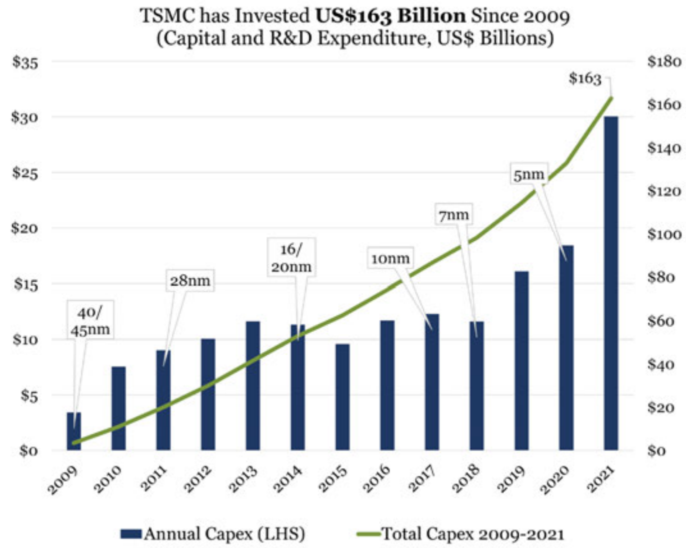
[107] Hass, Ryan, "This US-China downturn may be difficult for Taiwan," *Brookings Institution*, February 24, 2020, https://www.brookings.edu/blog/order-from-chaos/2020/02/24/this-us-china-downturn-may-be-difficult-for-taiwan/

[108] Cheng, Ting-Fang and Lauly Li, "TSMC says 2020 revenue to jump 30% despite losing Huawei orders," *Nikkei Asian Review*, October 15, 2020, https://asia.nikkei.com/Business/Technology/TSMC-says-2020-revenue-to-jump-30-despite-losing-Huawei-orders

[109] "Financial Results -2022 Monthly Revenue," *TSMC*, June 18, 2023, https://investor.tsmc.com/english/monthly-revenue/2021

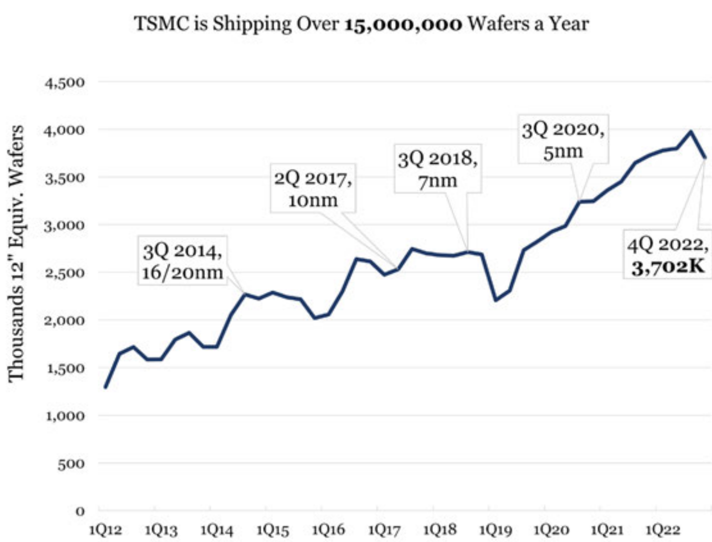
of last year that it has expanded its production at the 3 nm size, and that 2 nm mass-production could be just a few years away.[110] [111]

Figure 17: TSMC Capital and R&D Expenditures



Source: TSMC Annual Reports[112]

Figure 18: TSMC Annual Shipments



Source: TSMC Annual Reports

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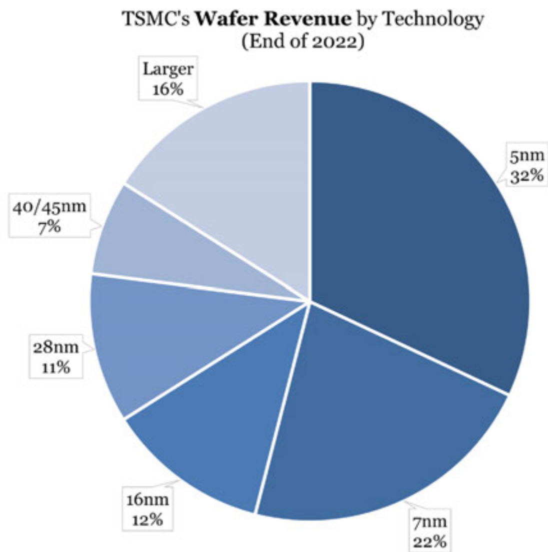
[110] "TSMC Holds 3nm Volume Production and Capacity Expansion Ceremony, Marking a Key Milestone for Advanced Manufacturing," *Taiwan Semiconductor Manufacturing Company*, News Archives, December 29, 2022, https://pr.tsmc.com/english/news/2986

[111] Friedman, Alan, "New report says TSMC is on schedule to mass-produce 2nm chips by 2025," *PhoneArena*, April 7, 2023, https://www.phonearena.com/news/tsmc-2nm-production-2025_id146771

[112] "Annual Reports," *TSMC*, https://investor.tsmc.com/english/annual-reports

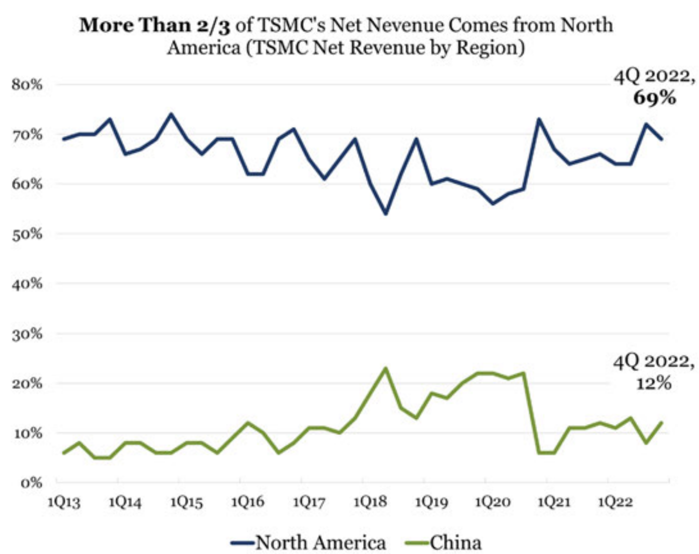
TSMC now ships nearly 15 million wafers a year, or just over 1 million wafers a month. Recently, the majority of TSMC's revenue has come from sales of the most advanced types of manufactured chips, as over 50% of TSMC's revenue comes from chips manufactured at 7 nm and 5 nm size. TSMC is also heavily dependent on the U.S. for its business, as nearly 70% of TSMC's sales come from North America. This has generally been the case except for a brief period between 2018 and 2020 when sales to China increased during the U.S.-China trade war.

Figure 19: TSMC's Wafer Revenue by Technology



Source: TSMC Annual Reports

Figure 20: TSMC Net Revenue by Region

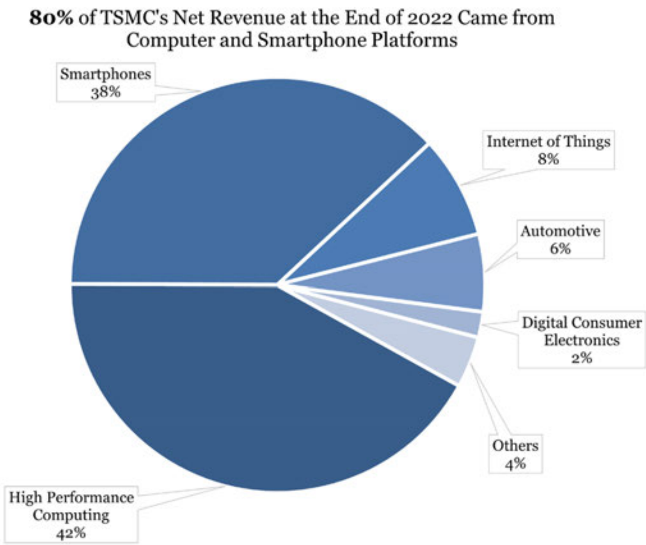


Source: TSMC Annual Reports

Most of TSMC's revenue (80%), comes from computer and smartphone platforms, but by some estimates TSMC also produces 35% of the world's automotive microcontrollers.[113]

Given its history of large investments, the number of investments made, the amount invested, and specialization the company has undertaken, TSMC is not a business that the U.S. or other countries could easily replace. Add to this that the cost of creating a TSMC facility is generally more costly outside of Taiwan.[114] In addition, the business culture and know-how to run a foundry is a skill not easily or widely available.[115]

Figure 21: TSCM Net Revenue from Computer & Smartphone Platforms



Source: TSMC Annual Reports

Taiwan Is a Critical Link

Taiwan may be ***the*** most critical link in the entire technology ecosystem. Foundries and associated businesses based in Taiwan serve as crucial supply partners to companies both in the United States and globally. As discussed earlier, Taiwan companies have a more than 60% foundry market share, and TSMC is one of only two companies that currently mass-produce chips at below 5 nm. In 2021, Taiwan was estimated to account for approximately 92% of all semiconductor production at process nodes less than 10 nm.[116] Traditionally, Taiwan foundries have mostly been involved in manufacturing semiconductor devices for global clients but have added significant design services to their portfolio in recent years.

In addition to foundries, six of the top 10 OSAT's by revenue are Taiwan companies, accounting for over 52% of the OSAT market.[117] The island serves as a semiconductor cluster and as a hub for every facet of the industry. That includes not only cutting-edge fabrication plants and OSAT services, but also key materials suppliers. Taiwan is a hub

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113 Vest, Charlie, Agatha Kratz, and Reva Goujon, "The Global Economic Disruptions from a Taiwan Conflict," *Rhodium Group*, December 14. 2022, https://rhg.com/research/taiwan-economic-disruptions/

114 Varas, Antonio et al., " Government Incentives and US Competitiveness in Semiconductor Manufacturing," op. cit.

115 Liu, John and Paul Mozur, "Inside Taiwan Chip Giant, a U.S. Expansion Stokes Tensions," *The New York Times*, February 22, 2023, https://www.nytimes.com/2023/02/22/technology/tsmc-arizona-factory-tensions.html

116 Varas, Antonio et al., "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era," op.cit

117 Khan, Saif, et al., "The Semiconductor Supply Chain: Assessing National Competitiveness," op.cit.

for Original Equipment Manufacturing (OEM) and Original Design Manufacturing (ODM), as well as a production center for many associated types of technology materials such as printed circuit boards. Taiwan currently serves as a key supplier and partner to many leading U.S. technology firms like Apple, Nvidia, Texas Instruments, and Qualcomm, as well as to many U.S. allies globally.

Potential risks to the semiconductor supply chain are especially acute in Taiwan, given its complex political and diplomatic situation and existing tensions with its neighbor across the Taiwan Strait. China increased its pressure on Taiwan in 2022, conducting record numbers of incursions by military aircraft in Taiwan's Air Defense Identification Zone (ADIZ), poaching diplomatic allies, and punishing countries like Lithuania or Czechia that have showed support for Taiwan.

A serious conflict in the Taiwan Strait could significantly and negatively impact not only Taiwan but also the rest of the world, including China. Compromising Taiwan's national security would negatively impact the global supply of semiconductors, and by extension the American, global, and Chinese economies. Some have argued that this confers on Taiwan a degree of protection like a "*Silicon Shield*" against an increasingly assertive China.[118] Others have called the standoff with China over access to semiconductors from Taiwan a new cold war, adding technological importance and an economic weight to Taiwan's already extensive geopolitical importance.[119] Some have even posited that Taiwan's advantages in semiconductors could increase Chinese desire for the island, potentially accelerating Beijing's timeframe for resolving Taiwan's status.

In addition, Taiwan is also subject to natural disasters such as earthquakes and other seismic events, typhoons, and drought, all of which present potential threats to the semiconductor supply chain. In August 2009, Taiwan was hit by Typhoon Morakot, causing devastating flooding and large losses for the agriculture and tourism sectors, while the technology and semiconductor sectors luckily escaped major impact. In September 1999, the devastating Jiji earthquake claimed over 2,000 lives and disrupted business across the island. Hsinchu Science Park, a center for semiconductor production, estimated earthquake losses at approximately US$355 million, and several semiconductor factories remained shut down for several days in the aftermath.

Taiwan is a critical link in the semiconductor supply chain, a partner for the U.S., and one that is also vulnerable to the semiconductor supply chain disruptions that we will discuss below.

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[118] Addison, Craig, "Silicon Shield: Taiwan's Protection Against Chinese Attack," *Fusion Press*, September 1, 2001

[119] Sharma, Ruchir, "Opinion: Pound for Pound, Taiwan Is the Most Important Place in the World," *New York Times*, December 14, 2020, https://www.nytimes.com/2020/12/14/opinion/taiwan-computer-chips.html

Disruptions to Taiwan's Semiconductor Production

The heart of this report is to try and estimate the importance of the Taiwan semiconductor industry to the U.S. economy. As we've already shown, the Taiwan semiconductor industry is essential to both the U.S. and global economies. But what are the kinds of disruptions that could impact the Taiwan semiconductor industry? What could a disruption mean for companies' timelines in an industry that generally operates continuously near max capacity and is production intensive?

Above, we have highlighted several vulnerabilities already seen in the semiconductor supply chain: design, supply, and demand vulnerabilities. These include issues such as a talent shortage, intellectual property and trade secrets theft, natural disasters, supply and demand gaps, and material, water, and power shortages. These all threaten the semiconductor industry as a whole and aren't necessarily specific to Taiwan.

When thinking about the types of disruptions to Taiwan's semiconductor industry, and how they could affect businesses, it's also important to consider the severity of the disruption and what sort of impact it could have on the manufacturing process. For example, the disruption caused by a typhoon or mild earthquake is less severe, but more likely, than the disruption caused by another global pandemic or an armed conflict.

In this report, we separate disruptions into their potential length of time. We break down the length of disruptions between partial disruptions (30 days), significant disruptions (4-10 months), and total disruptions (1+ years). We give examples of events that have generated various lengths of disruption. However, it's entirely possible that an event, such as an earthquake, has the potential to cause partial or significant damage. In general, an event that has the potential to cause partial disruption has a greater chance of happening. Events that could cause significant or a total disruption have a less likely chance of happening.

A partial disruption is the most likely disruption but also the least severe. A partial disruption means some segment of the industry has encountered an event which has stalled production for a short period of time (30 days or less). The problem is either fixed, companies dip into their inventories, or the disruption is mitigated by moving production to another facility. These kinds of disruptions still shouldn't be taken lightly. Even partial disruptions can have cascading effects to the supply chain if companies are unprepared. A two-week disruption can shut down facilities and even furlough workers if companies' inventories are low.[120]The types of events that have the potential to create partial disruption include severe weather, industrial accidents, transportation issues, and government restrictions.

Severe weather and natural disasters are a common threat to Taiwan's semiconductor industry. Given that Taiwan is located on the circum-Pacific seismic zone, also known as the "Ring of Fire," it experiences over 200 noticeable earthquakes a year and seasonal typhoons.[121] One of the largest earthquakes in Taiwan's modern history was a 7.6 magnitude shock in 1999 that did several hundred millions worth of damage and temporarily halted semiconductor production for nearly a week.[122] Semiconductor companies in Taiwan have generally invested to withstand severe weather incidents.[123] In the past few years, there have been several earthquakes over a magnitude of 6.0 that have only

[120] "Results from Semiconductor Supply Chain Request for Information," *U.S. Department of Commerce*, January 25, 2022, https://www.commerce.gov/news/blog/2022/01/results-semiconductor-supply-chain-request-information

[121] "FAQ for Earthquake-15. What is the frequency of earthquake occurrence in Taiwan?," *Central Weather Bureau Seismological Center*, https://scweb.cwb.gov.tw/en-US/Guidance/FAQdetail/190

[122] Moh, Za-Chieh et al., "1999 Chi Chi Earthquake of Taiwan," *MAA Group*, http://www.maa.com.tw/common/publications/2000/2000-037.pdf and Varas, Antonio et al., "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era," op.cit.

[123] "Earthquake Continuity Plans Surpassing Legal Requirements," *Taiwan Semiconductor Manufacturing Company*, https://esg.tsmc.com/en/update/governance/caseStudy/1/index.html

caused temporary disruption to production facilities.[124] But as the 1999 earthquake showed, earthquakes can disrupt the power system and other infrastructure these companies rely upon as well, adding to the complexity of industrial supply chains.

Drought is another concern for chip manufacturers. Water isn't just essential for the semiconductor manufacturing process but essential to the energy and infrastructure that power manufacturing facilities. In 2021, a severe lack of rainfall left Taiwan's water reserves depleted. While it doesn't appear to have caused any serious disruption to production, companies like TSMC still had to spend millions of dollars trucking in water to their facilities.[125]

Industrial accidents include all sorts of issues from machine malfunction to human error. A common industrial accident for the semiconductor industry is fire, given the mixed use of various flammable chemicals in an electrical environment. Fires have caused millions of dollars' worth of damages for semiconductor manufacturers in the past.[126] For example, in March 2021 a fire broke out at a Renesas Electronics Corporation semiconductor factory in Ibaraki, Japan, destroying 23 machines and contaminating part of its facilities. This fire contributed to a major auto chip shortage. It took Renesas a little over 2 months to restore 88% of its production capacity lost due to the fire.[127]

Man-made disruptions will always be a concern. This can include labor disputes, transportation problems such as port, trucking, and railway disruptions, and geopolitics and other government restrictions. For example, during the global pandemic, countries were closing their borders to prevent the spread of COVID-19, forcing companies to find alternative means for production and transportation. Shanghai, China, where many tech companies are located, was on lockdown for two months.[128]

There is also a concern about cyberattacks, but the disruption potential of these events is difficult to estimate. Cyber criminals and state-sponsored attackers have been known to target industries and infrastructure alike for either profit or acts of malice. In 2018, TSMC was a victim of the global WannaCry ransomware attack.[129] It reportedly cost the company US$250 million and shipment delays.[130] Taiwan semiconductor companies are also constantly the target of state-sponsored cyber espionage attacks originating in China.[131]

Other potential disruptions to the supply chain require additional data. For example, what would a shortage or restriction in trade of critical minerals and other gases could mean for Taiwan's semiconductor manufacturing? The kinds of restrictions on the flow of goods can often be political in nature. Given the geopolitical nature of these disruptions however, the length and severity of the disruption would vary.

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[124] "Work resumes at TSMC after quake evacuation," *Taipei Times*, March 24, 2022, https://www.taipeitimes.com/News/biz/archives/2022/03/24/2003775337

[125] Barbiroglio, Emanuela, "No Water No Microchips: What Is Happening In Taiwan?" *Forbes*, May 31, 2021, https://www.forbes.com/sites/emanuelabarbiroglio/2021/05/31/no-water-no-microchips-what-is-happening-in-taiwan/?sh=2132213622af

[126] Sherin, Brian. "Work Station Fire Protection for a Semiconductor Facility," *Professional Safety* 34, no. 12 (1989): 16–21., http://www.jstor.org/stable/45432846

[127] Kim, Chang-Ran, "Japan's Renesas sees fire-damaged chip plant back to full capacity by mid-June," *Reuters*, May 31, 2021, https://www.reuters.com/technology/renesas-restore-fire-hit-chip-plant-100-capacity-around-mid-june-2021-06-01/

[128] Jackson, Patrick and Zubaidah Abdul Jalil, "Shanghai lockdown: China eases Covid restrictions after two months," *BBC*, June 1, 2022, https://www.bbc.com/news/world-asia-china-61647687

[129] Lee, Yimou, "Apple chip supplier TSMC resumes production after WannaCry attack," *Reuters*, August 6, 2018, https://www.reuters.com/article/taiwan-tsmc-virus-idINKBN1KR0B9

[130] "Tower hit by cyber attack, some production disrupted," *Techtime*, September 6, 2020, https://techtime.news/2020/09/06/tower-semiconductor-2/.

[131] Greenberg, Andy, "Chinese Hackers Have Pillaged Taiwan's Semiconductor Industry," *WIRED*, August 6, 2020, https://www.wired.com/story/chinese-hackers-taiwan-semiconductor-industry-skeleton-key/

There are two scenarios that could potentially cause a more significant (4-10 month) disruption to the Taiwan semiconductor industry: an economic blockade and another global pandemic. An economic blockade would most likely be implemented by the People's Republic of China around Taiwan, as Beijing looks to restrict the flow of goods and services in and out of Taiwan.

There are multiple reasons that Beijing might take such an action. Beijing may either be upset with Taiwan's political leadership, or it may be upset with American support of Taiwan. This could lead Beijing to hold Taiwan's trade flows hostage as it makes demands, or it may preempt an invasion. These kinds of scenarios are hard to predict, however, given that there are several moving variables - including Taiwan's political and military response, the fact that Beijing would also threaten its access to Taiwan-made chips which it relies heavily on, and whether such an event would be of "grave concern" to the U.S., and thereby potentially forcing Washington to get involved.[132]

The second scenario that could cause a significant disruption is another global pandemic like the one the world experienced starting in 2020. Before the global pandemic, there was already a growing chip surplus as global growth was slowing.[133] Once the pandemic hit, however, demand shifted significantly. Demand for computers and personal electronics increased as more workers started working from home instead of in the office. Car manufacturers, which initially canceled their orders given an expected shortage of demand, had a hard time replacing those orders once they determined that demand for cars was picking back up. This led to a severe shortage in automotive-grade chips.[134] By one estimate, the chip shortage cost the global automotive industry US$210 billion in 2021.[135]

Defense and National Security

There is only one likely scenario that could mean a total disruption to the Taiwan semiconductor industry for a year or more: war. Despite the recent increase in ADIZ incursions and military exercises around Taiwan, it's debatable whether Beijing and the People's Liberation Army has any intent to invade Taiwan anytime soon. Even then, there's no consensus about what sort of damage an attempted invasion could cause or what a protracted war between China and Taiwan would look like.

It is important to remember too that China still relies on other countries for advanced chips, with a strong dependence on imports from Taiwan, despite long-standing and diligent attempts to develop its own indigenous semiconductor industry. Even the most advanced semiconductor companies in China are years behind TSMC in technological capability. This gap means that most consumer technology products made in China are also dependent on Taiwan semiconductors, thus introducing the risk of severe damage to Chinese companies as well, in the eventuality that the supply chain through Taiwan should be compromised by military action.

In a worst-case scenario of a Chinese invasion, all flow of goods and services in and out of Taiwan are stopped, manufacturing capacity is shut down, and Taiwan's semiconductor industry eventually comes under the control of the Chinese Communist Party. The immediate effect would be felt worldwide. According to the Office of the Director of National Intelligence's 2022 and 2023 Annual Threat Assessments, "*China's control over Taiwan probably would*

[132] The Taiwan Relations Act of 1979 states, "It is the policy of the United States to consider any effort to determine the future of Taiwan by other than peaceful means, including by boycotts or embargoes, a threat to the peace and security of the Western Pacific area and of grave concern to the United States" Taiwan Relations Act, Pub. L. No. 96-8, 93 Stat. 14 (1979).

[133] "World Economic Outlook, October 2019: Global Manufacturing Downturn, Rising Trade Barriers," *International Monetary Fund*, October, 2019, https://www.imf.org/en/Publications/WEO/Issues/2019/10/01/world-economic-outlook-october-2019

[134] Leswing, Kif, "What's causing the chip shortage affecting PS5, cars and more?," *CNBC*, February 10, 2021, https://www.cnbc.com/2021/02/10/whats-causing-the-chip-shortage-affecting-ps5-cars-and-more.html

[135] Wayland, Michael, "Chip shortage expected to cost auto industry US$210 billion in 2021," *CNBC*, September 23, 2021, https://www.cnbc.com/2021/09/23/chip-shortage-expected-to-cost-auto-industry-210-billion-in-2021.html

disrupt global supply chains for semiconductor chips because Taiwan dominates production."[136] The cost of war would be much higher than what's estimated in this report, however, given the nature of war, potential secondary sanctions, and a collapse in international relations with China.

A recent example of the effect war would have on the Taiwan semiconductor industry is the war in Ukraine. Since Russia's invasion of Ukraine in February 2022, the price of neon gas has increased dramatically.[137] As we have already discussed, Ukraine was a source for most neon gas used by global semiconductor manufacturers. Since the war began, neon has become scarce, driving up costs. Both Taiwan and China are much more integrated into the global economy that either Ukraine or Russia, especially for technology production. Therefore, war between Taiwan, China, and potentially the U.S. would be globally devastating.

Advanced semiconductors also play an important role in the defense industry. This is increasingly so as the U.S. military posture relies on relatively few high-quality systems containing advanced microelectronics. Due to the long lifecycle of many weapons systems, however, military systems generally tend to rely on older legacy chips. Many of those tend to still be produced in the United States. Case in point is the B-52, which is still flying some 50 years after its first flight. In many cases, the United States also leverages "lifetime buys" where it purchases all of the chips it needs to maintain a system over its estimated lifecycle. Nevertheless, some military systems — such as advanced avionics and supercomputers — still require access to state-of-the-art process technology.

The U.S. Department of Defense created a "Trusted Foundries Program" in 2004, intended to develop a network of trusted commercial suppliers for critical ICs used in DoD's weapons, intelligence, and communications systems. In 2007, the program expanded to include design and OSAT firms. As of spring 2022, the program had identified 81 accredited suppliers.[138] However, domestic U.S. production of semiconductors for the trusted foundry program is limited to 14 nm and above, which does not provide solutions for more advanced technologies on a trusted basis. DoD has said that the chips procured through the program is two generations behind what's available commercially, and they are committed to transition away from this model to a zero-trust model for procuring custom microelectronics - assuming that everything must be validated before use but allowing the department to procure commercial technologies. This transition appears to still be under way.[139] DoD has also established the "RAMP-C" program, which aims to leverage a public-private partnership with Intel that would potentially allow for DoD to access more advanced process nodes at 10 nm and below.[140]

While the Trusted Foundry Program may have been sufficient to satisfy the needs for exotic, low volume custom chips designed by the U.S. military, it is not sufficient to cover all the semiconductor procurement requirements of the U.S. military for more general-purpose chips. In 2016, the Trusted Foundry Program accounted for less than 2% of the ICs that DoD acquired per year.[141] Instead, many of the general-purpose semiconductors needed for advanced weapons

[136] "Annual Threat Assessment of the U.S. Intelligence Community," *Office of the Director of National Intelligence*, February 7, 2022, https://www.odni.gov/files/ODNI/documents/assessments/ATA-2022-Unclassified-Report.pdf and "Annual Threat Assessment of the U.S. Intelligence Community," *Office of the Director of National Intelligence*, February 6, 2023, https://www.armed-services.senate.gov/imo/media/doc/Unclassified%202023%20ATA%20Report.pdf.

[137] Guo, Jeff, "The war in Ukraine is disrupting the world's supply of neon," *NPR*, August 12, 2022, https://www.npr.org/2022/08/12/1117263854/the-war-in-ukraine-is-disrupting-the-worlds-supply-of-neon

[138] "Accredited Suppliers," *Defense Microelectronics Activity*, May 11, 2022, https://www.dmea.osd.mil/otherdocs/AccreditedSuppliers.pdf

[139] "Evaluation of the Department of Defense's Transition From a Trusted Foundry Model to a Quantifiable Assurance Method for Procuring Custom Microelectronics (DODIG-2022-084)," *Department of Defense Office of Inspector General*, May 4, 2022, https://www.dodig.mil/reports.html/Article/3019461/evaluation-of-the-department-of-defenses-transition-from-a-trusted-foundry-mode/

[140] "Intel Wins US Government Project to Develop Leading-Edge Foundry Ecosystem," *Intel*, August 23, 2021, https://www.intel.com/content/www/us/en/newsroom/news/intel-wins-us-project-develop-foundry-ecosystem.html

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

systems are developed by fabless companies in the U.S. and manufactured in Taiwan.

Semiconductor supply chain visibility is low in the defense sector, but analysts estimate that microelectronics attribute a significant portion of the value in current generation weapons systems. For example, Lockheed Martin's Javelin missiles each contain over 200 semiconductors, and TSMC manufactures some chips for the Javelin system.[142] A disruption to the supply chain involving Taiwan is therefore also likely to have severe repercussions for U.S. national security, given that semiconductors play such a key role in the advanced weaponry that the U.S. military relies upon for its defensive and offensive capabilities.

The U.S. government has also identified several sectors where potential disruptions could have a destabilizing impact on society, designating them as critical infrastructure.[143] These sectors include energy, transportation, financial services, and communications, among others. Many are especially dependent on technology, including advanced semiconductors. In particular, the telecommunications sector is heavily reliant on Taiwan semiconductor production.

Semiconductors for commercial and military applications are not necessarily mutually exclusive. Electronic components in sophisticated military systems use many of the same logic and memory chips that appear in consumer electronics. For example, Field Programmable Gate Arrays (FPGAs) are frequently used in military systems due to their low-cost and high modularity. Nevertheless, there are military-specific requirements that call for semiconductors with certain features. While commercial chip production is heavily driven by cost and timely, large-scale production, the defense sector emphasizes performance and reliability. Military-specific chips must be more durable and reliable, have a higher heat tolerance, operate at higher voltages, and in some cases must be radiation tolerant.

Many military-specific chips thus contain compound semiconductors that have superior electronic properties — such as high electron mobility and direct band gap — compared to silicon-only based semiconductors. Specifically, gallium arsenide (GaAs) and gallium nitride (GaN)-based chips appear most frequently in military-specific configurations. Radio-Frequency Integrated Circuits (RFICs) and Monolithic Microwave Integrated Circuit (MMICs) use GaAs and GaN technologies and are used in a wide range of defense and aerospace applications. These include electromagnetic spectrum operations, signals intelligence, military communications, space capabilities, radars, jammers, etc. The United States has a very strong domestic compound semiconductor sector and is largely self-sufficient for military-grade compound semiconductors. Nevertheless, Taiwan also plays a central role in producing commercial variants of compound semiconductors, primarily supplying products for the mobile communications market.

To illustrate, Taiwan's WIN Semiconductors holds 9.1% of the total GaAs device market share, which places it third in the world behind American firms Skyworks (30.6%) and Qorvo (28.6%). But in terms of pure-play GaAs foundry revenue, WIN Semiconductors held by far the largest share in 2020 at 79.2%. The next three firms are Tainan-based AWSC (8.6%), Torrance, CA-based GCS (4.2%), and Hsinchu-based Wavetek (3.4%).[144] Together, the top three Taiwan firms hold over 90% of the GaAs pure-play foundry market that is critical for cellphones and telecommunications base stations.

Aspects of the U.S. defense industrial base are reliant on some of Taiwan's semiconductor production for the same reason that the commercial sector is — the emergence of the fabless-foundry business model, and Taiwan's rise to become a hub for cutting-edge semiconductor manufacturing. Despite current private and public sector efforts in the U.S. to advance domestic semiconductor manufacturing capabilities, American defense and commercial critical

[142] Leading Edge Update Newsletter, *TSMC Government Affairs*, May 10, 2022

[143] "Critical Infrastructure Sectors," *Cybersecurity & Infrastructure Security Agency, Department of Homeland Security*, https://www.cisa.gov/critical-infrastructure-sectors

[144] "Win Semiconductors Corp," *Morningstar Ratings*, September 2021, https://www.morningstar.com/stocks/roco/3105/quote

infrastructure dependencies on Taiwan are unlikely to significantly decrease in the short term.

The immense costs of maintaining and advancing state-of-the-art fabs is a key reason for this, considering that one of TSMC's forthcoming Arizona fabs is estimated to cost roughly the same as the U.S. Navy's Ford-class aircraft carrier. While the recently passed CHIPS and Science Act allocated US$52.7 billion for domestic semiconductor manufacturing and R&D in the U.S., TSMC alone intends to spend US$100 billion over the next several years.[145]

The fabless-foundry model has allowed U.S. tech companies like Nvidia and Apple to rise to the top of the commercial market. However, U.S. reliance on this model has also led to issues surrounding supply chain security in the defense sector. Today the largest U.S. manufacturer of GaAs semiconductors is Skyworks, a fabless firm that utilizes Taiwan's WIN Semiconductors for some of its foundry services. Similarly, the largest producers of FPGAs are American firms Xilinx, Lattice, Intel, and Microchip Technologies. The first two are fabless and rely on Taiwan chipmakers TSMC and UMC as its primary manufacturing contractors. Even Intel relies on its own partnership with TSMC to manufacture some of its most advanced chips.

Taiwan-made chips provide critical functionality for advanced U.S. systems, and strategic technologies — including quantum computing and artificial intelligence — rely on advanced semiconductors. The U.S. military could likely weather disruptions to their supply chain in a peacetime environment, but disruptions to production ahead of and during wartime could lead to significant and negative consequences for American forces. Wartime semiconductor supply chain disruptions in Taiwan could impact production, maintenance, repair, and overhaul at least two to five tiers upstream in the supply chain.

Yet the reality is that U.S. military needs for chips is a drop in the bucket in comparison to the overall demand in the global semiconductor industry, including for many vital commercial sectors such as banking, energy, and telecommunications –all vitally important to the United States. Due to consumer and market demands, the commercial sector has drastically outpaced national security focused requirements when it comes to innovation and cutting-edge technology. Gone are the days of ARPANET; the U.S. defense sector has little sway in steering semiconductor trends, and bases much of its systems on existing commercially available platforms.

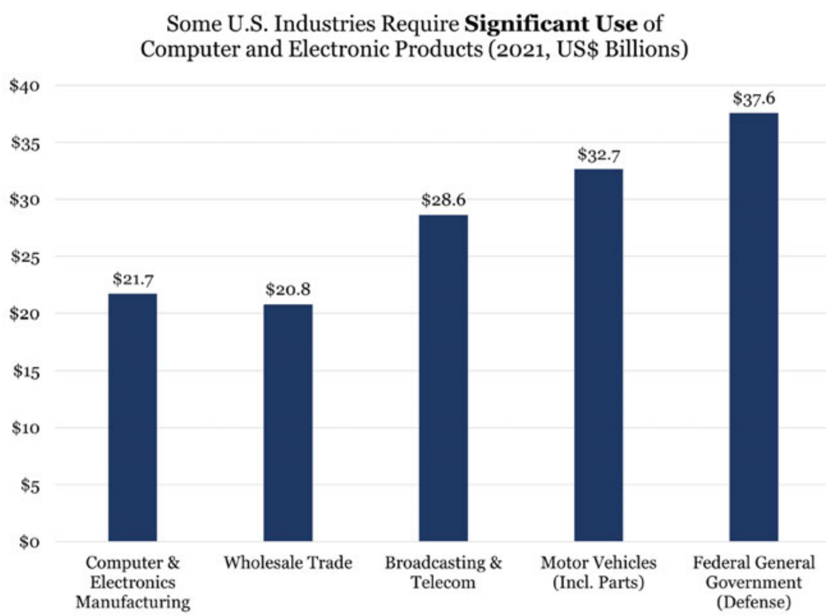
Defense technologies are trending toward more integrated and unmanned platforms, and advanced semiconductors will be increasingly central to future weapons systems. As the U.S. military grows ever more reliant on American commercial technology firms — who in turn rely on Taiwan chip manufacturing — a path forward could be closely coordinating and integrating the U.S. and Taiwan defense and technology sectors. The United States and Taiwan would do well to explore co-development and co-production of next generation defense platforms, a win-win situation.

[145] "TSMC to Spend US$100 Billion Over Three Years to Grow Capacity," *Bloomberg*, April 1, 2021, https://www.bloomberg.com/news/articles/2021-04-01/tsmc-to-invest-100-billion-over-three-years-to-grow-capacity

The Economic Cost of Losing Access to Taiwan Chips

Our modern economy relies on the constant supply of semiconductor devices and electronics. Many U.S. industries require the significant use of computers and electronic products. Semiconductors are required in the manufacturing of computers, smartphones, cars, data centers, and in other industries that use electronics like farming, retail, healthcare, and so on.

Figure 22: U.S. Industries Reliant on Computer & Electronics Products



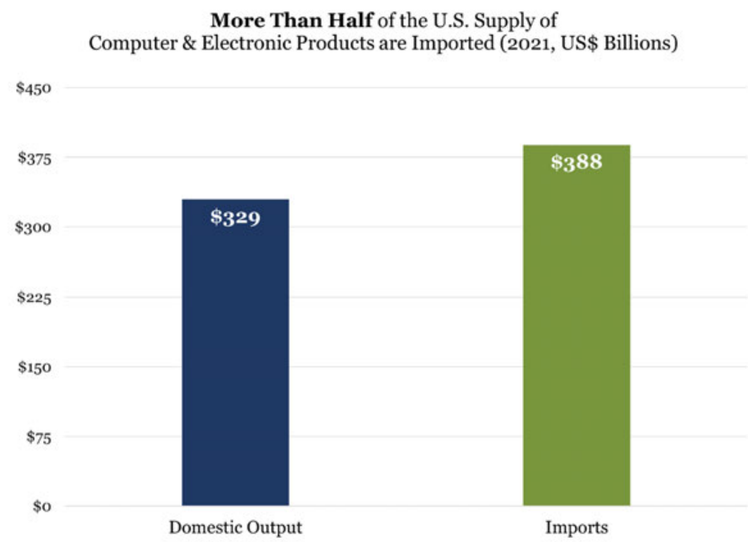
Source: Use of Commodities by Industries, U.S. Bureau of Economic Analysis[146]

The four industries that rely the most on computer and electronics products are the computer and electronic manufacturing industries, broadcasting and telecommunications, motor vehicle manufacturing, and national defense. Each one of these industries used over US$20 billion worth of computer and electronic products in 2021. Meanwhile, more than half of the U.S. supply of computer and electronic products are imported, and much of which comes from China.

Looking at added value, these four industries represent roughly US$1.6 trillion in value or 7.8% of U.S. GDP.

[146] The Use of Commodities by Industries, *U.S. Bureau of Economic Analysis*, https://www.bea.gov/data/industries

Figure 23: Composition of U.S. Supply of Computer & Electronic Products



Source: Use of Commodities by Industries, U.S. Bureau of Economic Analysis

It's unlikely that a significant disruption to the Taiwan semiconductor industry would completely shut down the U.S. operations of these four industries. However. national defense - while not entirely dependent on Taiwan-made chips for its weapons systems - still uses over-the-counter electronics and screens that likely include Taiwan-made chips. Other industries could continue to produce, even if at a slower rate, without these chips but not without significant costs to production.

It should be noted, however, that this chart does not include the multitude of other industries that also rely on various computer and electronic products that contain chips made in Taiwan. Such sectors include healthcare, other forms of transportation, infrastructure, data centers, farming, and more. Given this, a disruption negatively impacting about 8% of U.S. GDP may actually be a low estimate.

On a historical basis, this level of disruption would be on par with the last two major economic recessions seen in the U.S. The 2008-2009 global financial crisis negatively impacted the U.S. economy by roughly 6.3% of GDP. The 2020-2023 global pandemic negatively impacted the U.S. economy by roughly 7.5%. Of course, the long-term effects of these events are different. For example, many are still feeling the effects of the global pandemic. The long-term effect of American companies' inability to access Taiwan-made chips would be difficult for manufacturers to recover from.

Estimating the significance of Taiwan's semiconductor industry to the U.S. and global economies can be difficult. There have been other attempts to estimate the impact if Taiwan's economy and/or its semiconductor industry were to be disrupted. One study estimates that a one-year suspension of Taiwan's semiconductor exports could cost the world 1% of GDP.[147] Specifically, the U.S. and China would see the most damage with the U.S. losing 0.9% of GDP and China losing 1.5% of GDP on an annual basis.

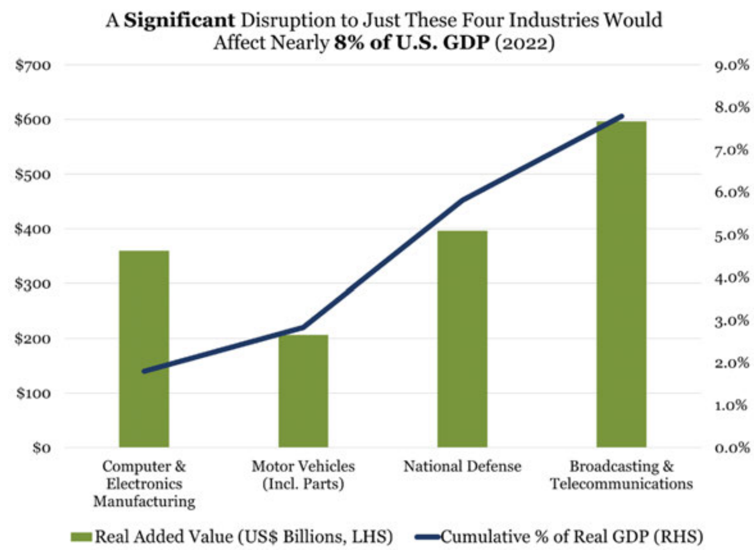
The projected impact was similar to an assessment by the U.S. Director of National Intelligence Avril Haines who,

[147] Nogimori, Minoru, "台湾情勢緊迫化と高まる半導体リスク," *The Japan Research Institute*, Research Focus No. 2021-023, August 6, 2021, https://www.jri.co.jp/MediaLibrary/file/report/researchfocus/pdf/12810.pdf

during Congressional testimony, suggested that a Chinese invasion of Taiwan that would halt the production of chips could wipe US$1 trillion from the global economy.[148]

According to another study, Japan - which is also heavily dependent on semiconductors from Taiwan - could potentially see a 1.4% decrease in its GDP.[149] Another estimate suggests that US$1.6 trillion in annual revenue could be lost in the event of a blockade around Taiwan.[150] Nearly US$1 trillion of that US$1.6 trillion revenue gap could fall on the U.S. alone.[151] Finally, another estimate suggests it would take at least three years and cost US$350 billion to simply replace the lost foundries in Taiwan if they were to ever become inaccessible.[152] This does not, however, include the cost to production if manufacturers are shut down from a disruption.

Figure 24: Potential U.S. GDP Impact of a Significant Disruption



Source: Real Value Added by Industry, U.S. Bureau of Economic Analysis[153]

Loss of access to Taiwan's semiconductor industry wouldn't have a significant impact just on those industries that rely upon semiconductor devices for their products, but also for the industries that sell their products to Taiwan's semiconductor industry. Given that Taiwan is one of the leading places for semiconductor manufacturing, it's also a market that's important for semiconductor equipment manufacturers.

Applied Materials, Lam Research, and KLA Corporation aren't just some of largest semiconductor equipment manufacturers in the U.S. but in the world. Their respective revenues in 2022 were US$25.8 billion, US$17.2 billion,

[148] "Top US spy says Chinese invasion halting Taiwan chip production would be 'enormous' global economic blow," *Reuters*, May 4, 2023, https://finance.yahoo.com/news/top-us-spy-says-chinese-173322685.html

[149] Kiuchi, Toei, "台湾有事の経済損失試算：国内GDP1.4%下落," *Nomura Research Institute*, Global Economy & Policy Insight, August 4, 2022, https://www.nri.com/jp/knowledge/blog/lst/2022/fis/kiuchi/0804_2

[150] Vest, Charlie, et al, "The Global Economic Disruptions from a Taiwan Conflict," op.cit.

[151] The rough estimate of US$1.6 trillion in annual revenue loss by Rhodium Group is based on company revenues that source from TSMC. In 2021, roughly 66 percent of TSMC's sales were from North America.

[152] Varas, Antonio et al., "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era," op.cit

[153] Real Value Added by Industry, *U.S. Bureau of Economic Analysis*, https://www.bea.gov/data/industries

and US$9.2 billion.[154] These are comparable with revenue reported by ASML (Netherlands) which had roughly US$22.3 billion and Tokyo Electron which had roughly US$15.2 billion in 2022.[155] Each one of these companies relies upon the Taiwan market for anywhere between 17% and 38% of their annual revenue. For example, Applied Materials gets 20% of its sales from TSMC alone.[156]

Table: Impact on Equipment Manufacturers

Company	**Revenue/Net Sales 2022**	**Percent of Sales in Taiwan**
Applied Materials	$25.8 billion	24%
Lam Research	$17.2 billion	17%
KLA Corporation	$9.2 billion	27%
ASML	$22.3 billion	38%
Tokyo Electron	$15.2 billion	18%
Total Value		**$22.8 billion**

It's hard to say what the impact would be on these companies if they were no longer able to access the Taiwan semiconductor market. It would be a huge hit to their annual revenue, business partnerships, with additional impacts to companies with facilities located in Taiwan. But it's not hard to imagine that some of these companies would face a complete loss as the U.S. government and other governments around the world intervene and subsidize new capacity in a worst-case scenario. It would take several years to replace this lost revenue.

The Potential Impact on U.S. Capital Markets

A corollary to the negative impact of supply chain disruptions on these sectors and companies would be the severe effect such a scenario is likely to have on U.S. capital markets. Major U.S. companies included in the Dow Jones Industrial Average - such as Apple, Microsoft, Google, Cisco, and Nvidia - would be severely impacted and their revenues would consequently suffer.

We have already established that the global pandemic might serve as an instructive example for the types of effects we could expect to see from a disruption to the Taiwan chip supply. In 2020, at the height of the pandemic crash, the Dow Jones index lost 37% of its value, while the S&P 500 lost 34%. At the same time, indexes in the UK, Germany, and Japan all posted double-digit percentage declines.[157] There is no doubt that we would see the same sorts of declines, if not even more severe, should the U.S. lose access to Taiwan chips.

154 "2022 Annual report with 10-K," *Applied Materials*, https://ir.appliedmaterials.com/annual-report-proxy, "2022 Proxy & Annual report," *LAM Research*, https://investor.lamresearch.com/annual-reports-and-proxy, and "2022 Annual Report," *KLA*, https://ir.kla.com/financial-information/annual-reports

155 "2022 Annual Report," *Advanced Semiconductor Materials Lithography*, https://www.asml.com/en/investors/annual-report/2022 and "Integrated Report 2022," *Tokyo Electron*, https://www.tel.com/ir/library/ar/f3pkth0000000gy2-att/IR2022_all_En.pdf

156 "2022 Annual report with 10-K," *Applied Materials,* https://ir.appliedmaterials.com/annual-report-proxy

157 Rodini, Laura, "What Was the COVID-19 Stock Market Crash of 2020? Causes & Effects," *The Street*, November 9, 2022, https://www.thestreet.com/dictionary/c/covid-19-stock-market-crash-of-2020

Outlook 2027

New manufacturing capacity is coming online every day, whether it's from an expectation that demand for semiconductor devices will increase or because governments across the world are handing out subsidies to encourage domestic investment. There will be more chips produced in 2027 than in 2022. Intel, for example, has announced plans to invest US$20 billion in Ohio, US$30 billion in Arizona, and 80 billion euros across the European Union over the next decade.[158] Samsung Electronics announced a US$17 billion expansion in Texas, and also plans to invest US$230 billion in South Korea over the next two decades.[159] TSMC has announced investments worth US$40 billion in Arizona, US$4.5 billion in Kumamoto, Japan, and billions more in Taiwan.[160]

Companies are constantly adjusting to reduce disruptions to their supply chains beyond building new capacity. More and more companies, and not just semiconductor manufacturing companies, are building redundancy into their supply chains. They're setting up risk management teams to prepare for all sorts of potential disruptions. Companies are working closer with their suppliers and building greater inventory, even at a cost. They're improving tracking and preparing alternative routes for delivery. Supply chains are becoming more geographically conscious. So, what would happen if a disruption to Taiwan's semiconductor industry were to happen in 2027 given all these preparations?

By 2027, it's fair to assume that there will be substantial demand for semiconductors produced at the then-leading 3 nm manufacturing process. Some of that production capability will be available at the TSMC plant being built in Arizona, meaning a disruption to the Taiwan semiconductor industry may have less of an impact on those products (particularly electronics) that rely on the 3 nm process. But by then, there will also be greater demand for all chips, including other than state-of-the-art chips made in Taiwan. A significant supply shock would be unavoidable. The U.S. and the global economy wouldn't be able to avoid a significant disruption if the Taiwan semiconductor industry were to be removed from the global supply chain.

As we look into the future, there are a few variables to consider that might impact the outlook for 2027.

Variable: Chip Shortage

As discussed above, changes in demand can be disruptive to the semiconductor supply chain. Early in the global pandemic, the demand for automobiles decreased because many people lost their jobs and those that kept their jobs increasingly worked from home. In addition, the massive shift to a work-from-home model across the globe led to increased demand for computing devices, while lockdowns and isolation orders led to an increase in demand for consumer electronics.

Conventional wisdom in supply chain management is to keep inventories low. Automotive companies therefore cancelled their existing orders for the chips needed to manufacture cars, while also reducing their orders for chips going forward. At the same time, consumer electronics and computer manufacturers placed orders for more chips to support the increased demand. This shift meant that many semiconductor manufacturers transitioned their capacity away from supporting the automotive industry, and towards supporting the consumer and business markets. As the

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[158] "Intel Corporation form 10-K for the fiscal year ended December 31, 2022," *Intel Corporation*, 2022, https://www.intc.com/filings-reports/all-sec-filings/content/0000050863-23-000006/intc-20221231.htm

[159] " One year since Samsung Electronics' Taylor expansion announcement," *Samsung*, November 28, 2022, https://www.samsung.com/us/sas/News/Detail/202211280901001_News_2022TaylorYear and Ouz, "Samsung Electronics Announces US$230 Billion Investment in the World's Largest Chip Factory," *GIZMOCHINA*, March 15, 2023, https://www.gizmochina.com/2023/03/15/samsung-electronics-worlds-largest-chip-factory/

[160] "2022 Fourth Quarter Earnings Conference," *Taiwan Semiconductor Manufacturing Company*, January 12, 2023, https://investor.tsmc.com/english/encrypt/files/encrypt_file/reports/2023-01/92c560bc8693eb0e57efc21d3b6b162dad8afafe/4Q22Presentation%28E%29.pdf and Manners, David, "Japan to give €3.5bn subsidy for TSMC fab," *Electronics Weekly*, June 17, 2022, https://www.electronicsweekly.com/uncategorised/japan-give-e3-5bn-subsidy-tsmc-fab-2022-06/

pandemic went on, the U.S. government provided economic stimulus through the 2020 Coronavirus Aid, Relief, and Economic Security (CARES) Act along with the American Rescue Plan Act of 2021. As the U.S. economy strengthened, and as concerns over public transportation during a pandemic affected public preferences, the demand for automobiles grew. The demand for other consumer products requiring chips also increased, while the demand for personal and business computing devices remained high. The chip shortage was a result of these increases in demand.

On the supply side, there were also several major disruptions that have contributed to the current chip shortage. Semiconductor manufacturers – and, just as importantly, their suppliers – experienced labor and supply issues due to the pandemic. The cost of silicon has also risen substantially.[161]

Two fires at a package substrate plant in Taiwan in October 2020 and February 2021 aggravated the global capacity shortage for assembly, packaging, and testing services, which was already experiencing difficulties to meet the surge in semiconductor demand in the last few months of 2020. Widespread power failures following a polar vortex in Texas that shut down Samsung, Infineon and NXP fabs (10% of U.S. capacity), and a shutdown of a Renesas fab (30% automotive market share) in Japan due to an earthquake in early 2021 further exacerbated the global chip supply shortage, especially for the automotive market.[162]

While the chip shortage that was so disruptive during the global pandemic has abated somewhat, its effects are likely to linger – particularly as certain types of chips remain in high demand.

Variable: Potential for Overinvestment

Given our increasingly digitized society and the growth of industries like AI and the Internet of Things (IoT), it is likely that we will see a sustained and growing future demand for semiconductors. Consumer and business products that traditionally have not required chips are now including them, while other products require both more and more advanced chips than in the past. Meanwhile, the chip shortage has the automotive sector, along with many other companies and governments around the world, looking for expanded chip capacity and access to more chips. In response, Intel, TSMC, and Samsung are all looking at building new fabs on U.S. soil, to take advantage of government incentives, while companies are also continuing to invest in other parts of the world.

The semiconductor industry is notoriously cyclical, with boom or bust cycles seen consistently over the last 40 years. The ups and downs of these chip cycles are mostly driven by the law of supply and demand. In times of high demand chip companies have trouble keeping up, which leads to pressure to build new capacity by building more fabs. Then when the overall economy slows — leading to decreased demand for chips – or if too much additional capacity is brought online at once, prices for chips fall and ultimately so do manufacturing levels.[163] The problem is worse for the semiconductor industry than for other industries, because a new wafer fab is both very expensive and takes several years to bring online. In addition, each new fab brings on a significant amount of capacity at once. When multiple companies add fab capacity and surge inventory levels, the supply can exceed demand – thereby leading to a bust.

Some analysts posit that the chip shortage was driven by a short term and artificial uptick in demand — one that is likely to fade by itself as the pandemic wanes, even without the semiconductor industry adding additional infrastructure and capacity. This could mean that current new fab construction would be completed in the 2024-2025 timeframe, when the pandemic-related demand pressures may have already dissipated. In addition, past boom-and-

[161] "The 2021 Semiconductor Chip Shortage: What, Why, and What's Next?," MAU Workforce Solutions, A. Pizzemento, April 15, 2021, https://www.mau.com/workforce-insights/the-2021-semiconductor-chip-shortage-what-why-and-whats-next

[162] "Chip plants halt work due to Texas storm and Japan earthquake," *fierceelectronics.com*, M. Hamblen, Feb 19, 2021, https://www.fierceelectronics.com/electronics/chip-plants-halt-work-due-to-texas-storm-and-japan-earthquake

[163] Seitz, P., "Semiconductor Companies: Where Are They In The Chip Cycle?," *Investor's Business Daily*, June 15, 2021, https://www.investors.com/news/technology/semiconductor-companies-semiconductor-industry/

bust cycles have been seen as not really a function of demand drying up, but rather being driven by surges in inventory levels and fab capacity on the supply side.[164]

The current pressure on semiconductor companies to increase capacity may end up driving a future bust, and there is a potential for overinvestment at this point in the cycle. However, companies and governments still appear willing to invest today — apparently making the strategic calculation that a steadily rising demand for chips will be able to offset the increased capacity and thereby forestall a potential future supply glut.

Variable: Government Policies

While the U.S. semiconductor industry still has nearly half the global market share and continues to have steady annual growth, it now has only a 12% share of semiconductor manufacturing capacity — down from 37% in 1990. Instead, three-quarters of the world's chip manufacturing capacity is concentrated in Asia. This is in large part because Asian governments have provided significantly more manufacturing incentives and more investments in chip research than the U.S. government over the same period.

As the U.S. investment in the industry has stayed flat (as a percentage of GDP) over the past 20 years, China has dramatically ramped up their investments in the industry and are projected by some to have the largest share of global chip production by 2030. China continues to focus on semiconductors as part of its overarching industrial policy, offering numerous tax and other incentives to its domestic chip companies, and providing substantial amounts of funding, trying to produce up to 70% of the chips it needs by 2025.[165]

The U.S. must maintain a leadership role in this critical industry for both economic and security reasons. U.S. government investments in the industry are needed to level the playing field, and such investments would also support new, high-paying jobs in the United States. This would also facilitate innovation and support development of the next generation products and technologies needed to support our economy, reduce costs to meet our clean energy goals, and provide for our national security.

The CHIPS and Science Act, enacted on August 9, 2022, aims to enhance U.S. competitiveness, innovation, and national security by introducing beneficial incentives. The law intends to stimulate investments in domestic semiconductor production capabilities while also propelling the advancement and practical implementation of cutting-edge technologies like quantum computing, AI, clean energy, and nanotechnology. Furthermore, it seeks to establish new regional high-tech centers and foster a larger, more diverse workforce in the fields of science, technology, engineering, and math (STEM).

The CHIPS and Science Act allocates a total of US$280 billion in expenditures for the upcoming decade. The primary portion of US$200 billion is designated for scientific R&D as well as for commercialization efforts. Additionally, US$52.7 billion is designated for semiconductor manufacturing, R&D, and workforce training, accompanied by US$24 billion in tax credits specifically aimed at promoting chip production. Furthermore, US$3 billion is earmarked for programs targeting cutting-edge technologies and the development of wireless supply chains. The Department of State was allocated US$500 million ($100 million per year over five years, starting in Fiscal Year 2023) to provide for semiconductor supply chain security and international information and communications technology (ICT) security.[166]

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164 Blodgett, Danny, 'What's next for Semiconductors? Be wary of those who say, 'This is a new paradigm',' *Omdia*, May 28, 2021, https://omdia.tech.informa.com/blogs/2021/whats-next-for-semiconductors-be-wary-of-those-who-say-this-is-a-new-paradigm

165 "Taking Stock of China's Semiconductor Industry," *Semiconductor Industry Association*, July 13, 2021, https://www.semiconductors.org/wp-content/uploads/2021/07/Taking-Stock-of-China%E2%80%99s-Semiconductor-Industry_final.pdf

166 "Fact Sheet: CHIPS and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China," *White House*, August 9, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/

On February 28, 2023, the Department of Commerce (DOC) announced the first round of manufacturing incentives related to the CHIPS and Science Act. This represents the first stage of funding from the DOC and is aimed at companies seeking assistance from the U.S. government to establish, expand, or modernize commercial facilities to produce advanced, current-generation, and mature-node semiconductors. These projects encompass both front-end wafer fabrication and back-end assembly, packaging, and testing. Two additional funding phases for semiconductor development will be introduced later in the year: one focusing on upstream suppliers and equipment manufacturers, and another targeting research and development initiatives in the semiconductor sector. Many U.S. and foreign companies, including TSMC, is evaluating the value of their participation and determining if they will requests to receive these incentives.

Other countries around the globe are also drafting and passing incentive plans to draw in semiconductor investment. Initiatives outside the U.S. include the United Kingdom through its UK Science and Technology Framework, the European Union through its EU Chips Act, along with additional funding for the domestic semiconductor industries in China, Taiwan, Spain, and India, among others.[167]

[167] "Global Semiconductor Funding Round-up - April 2023," *IES Engineering Services*, April 2023, https://www.ies.co.uk/news/global-semiconductor-funding-update-april-2023

Conclusions

The semiconductor industry is of vital importance to both the U.S. economy and to U.S. national security. The industry is the backbone of the digital economy and influences virtually every aspect of modern life. Semiconductors are vital components of our modern economy, and their significance will only continue to grow as we rely more on new technologies. Industries such as computers and electronics, automotive, telecommunications, and defense rely heavily on the continuous supply of advanced electronic components. Together, these industries contribute US$1.6 trillion, or roughly 8%, to the U.S. Gross Domestic Product (GDP).

Except for a brief period in the 1980's, the U.S has historically been the leader in this important industry. While the U.S. is still in a leadership position, the semiconductor ecosystem has grown to become truly global, and relies on the specialized capabilities from different geographic areas. It is therefore important for the United States to maintain strong relationships with strategic partners and to ensure that the semiconductor ecosystem can minimize the number and magnitude of disruptions to the supply chain.

Key among these strategic partners is Taiwan, due to its outsized influence on the sector and its unique geopolitical challenges. U.S technology firms, critical infrastructure suppliers, and the U.S. Department of Defense rely heavily on Taiwan foundries (particularly TSMC) to manufacture the computer chips needed for their products. This is particularly true for products that require chips that must be produced at 5 nm or below, since only TSMC and Samsung (South Korea) can currently produce chips at this level of sophistication.

The world is heavily dependent on Taiwan's semiconductor industry. It would take years, cost hundreds of billions of dollars, and immeasurable talent and knowledge to try to even replicate what Taiwan's semiconductor industry currently possesses. But some governments around the globe are trying, including the U.S. government. Lawmakers are investing billions of dollars to try and build more domestic capacity with the hope of mitigating the next disruption to the semiconductor supply chain.

Disruptions to the semiconductor industry come in all shapes and sizes, from severe weather events to large swings in demand to potential armed conflicts. New capacity may not be able to mitigate the types of disruption we discuss in this report. Even as new capacity comes online, demand is expected to continue growing as well. A significant disruption to the chips supply coming out of Taiwan would therefore not just shut down current production of personal electronics, telecommunications products, automakers, and computer manufacturers, but it would seriously cripple efforts to develop emerging areas like autonomous systems, electric vehicles, artificial intelligence, cloud computers, infrastructure, and defense. It would be one of the greatest disruptions to the U.S. and global economies seen in modern times. Taiwan's semiconductor industry will therefore remain indispensable to the U.S. economy.

The bottom line is that disruptions to Taiwan's semiconductor industry would have a significant impact on the U.S. and global economy. While the likelihood of a complete disruption is low, it underscores the vital importance of Taiwan's semiconductor industry to the U.S. economy. Taiwan will remain a critical partner for the foreseeable future, and the U.S. must do everything it can to ensure that Taiwan remains a close ally.