PROJECT 2049 INSTITUTE

US TAIWAN BUSINESS COUNCIL

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

Initial Report

June 8, 2022

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US TAIWAN BUSINESS COUNCIL

About the US-Taiwan Business Council

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.

This report serves as one way for the Council to offer analysis and information in support of our members' business activities in the Taiwan market. The publication of this report is part of the overall activities and programs of the Council, as endorsed by its Board of Directors. However, the views expressed in this publication do not necessarily reflect the views of individual members of the Board of Directors or Executive Committee.

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Executive Summary

U.S.-China trade issues, the pandemic, and recent shortages in automotive manufacturing 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. needs 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 nanometer (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.

Given its current structure, 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 an 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.

Given the importance of this industry, 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 — could work to bend the curve slightly. However, it will likely take significant time and massive investments to realize a positive outcome. The CHIPS for America Act is a good first step in supporting the U.S. semiconductor industry, and once fully funded should serve as an incentive for companies such as TSMC, Samsung, and Intel to build leading-edge semiconductor fabrication facilities on U.S. soil. Similarly, the proposed FABS Act should be expanded to include tax credits on expenditures for both manufacturing and design, to help strengthen the overall U.S. position in the crucial semiconductor sector.

This report, a joint effort by The Project 2049 Institute and the US-Taiwan Business Council, provides an initial look at vulnerabilities in the semiconductor supply chain, with a particular focus on Taiwan as a crucial partner for the U.S. in the semiconductor sector. It is part of an ongoing study of potential implications of technology supply chain disruptions involving Taiwan, a project that will later result in a final report – likely in 2023.

This joint project is ongoing, and project staff is currently conducting literature reviews and holding interviews with key industry and government leaders both in the U.S. and Taiwan. The final report will address a set of nine questions that fall into four main categories: 1) sources of disruptions in the semiconductor supply chain and the implications of such disruptions to the supply chain connecting Taiwan and the U.S.; 2) the impact of disruptions in the Taiwan-U.S. semiconductor supply chain on the U.S. economy and financial markets; 3) the impact of disruptions in the Taiwan-U.S. semiconductor supply chain on U.S. national security; and 4) how the U.S.-Taiwan semiconductor supply chain can become more resilient and/or be utilized to provide a pressure point to influence China's behavior.

This project, and the resulting final report, is intended to examine technology and semiconductor supply chain security as a pillar of the U.S.-Taiwan nexus — joining democracy and national security as foundational mainstays of shared interest and bilateral ties. That in turn is likely to broaden the constituency of support for Taiwan in the U.S., including in the business community and in Congress. We will also offer recommendations for the U.S. government and U.S. companies on mitigation strategies for the vulnerabilities identified.

Introduction

Integrated Circuits (IC's) were first developed in the late 1950's, and 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. Today, semiconductors are ubiquitous. They are the drivers of innovation in consumer electronics, automobiles, communication devices, computing, medical devices and healthcare, transportation, and in modern weapon systems.

Over the past three 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 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 50% market share and sales of US$208 billion in 2020.[3] There are currently around 277,000 direct semiconductor jobs in the U.S. semiconductor industry and 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 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$55.21 billion in semiconductors in 2020.[5] The U.S. also maintains a consistent trade surplus in semiconductors, including with major partners such as China.

Advanced semiconductors also 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.

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.

[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] "2021 State of the US Semiconductor Industry," *Semiconductor Industry Association*, 2021, https://www.semiconductors.org/wp-content/uploads/2021/09/2021-SIA-State-of-the-Industry-Report.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] "Export value of semiconductors from the United States, from 2002 to 2020," *statista.com*, https://www.statista.com/statistics/221762/us-exports-of-semiconductors-to-world/

The semiconductor supply chain is both complex and globally distributed, involving thousands of companies across the world. For the most part, the supply chain is performing well, and has led to the development of more advanced technology products at cheaper prices. Due to its complexity, however, it is vulnerable to potential disruptions. Any such disruptions could have substantial negative effects on governments, companies, and consumers both in the United States and around the globe, particularly as demand for semiconductors continues to outpace available supply.

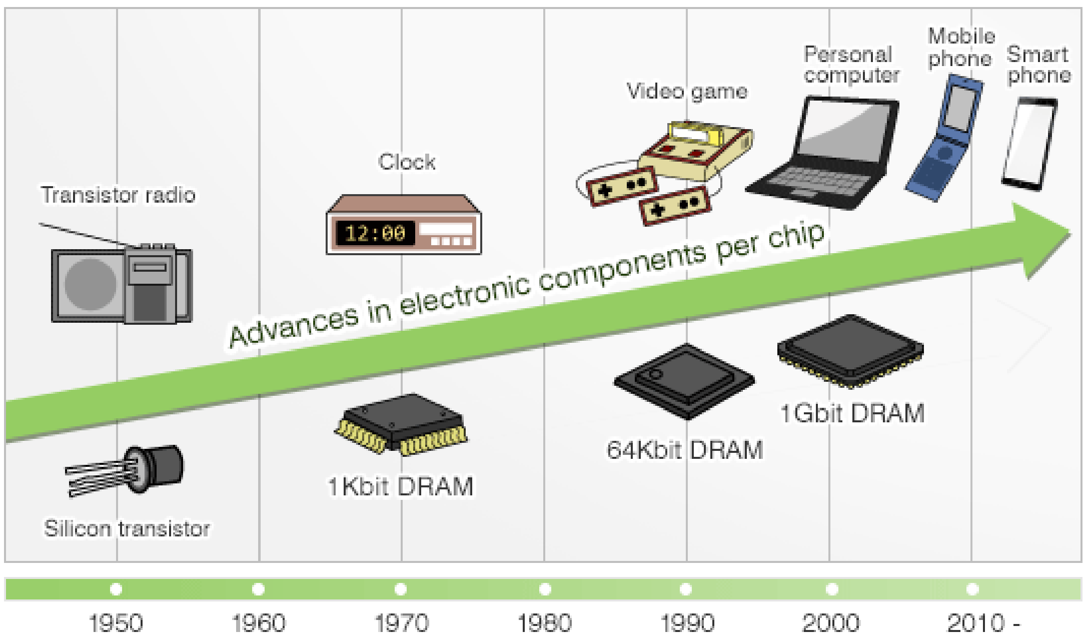
This report will examine those potential disruptions, with a particular focus on Taiwan. Taiwan is one of several key global semiconductor leaders, a crucial partner for the U.S., and is also subject to a specific set of challenges that exemplifies the variety of risks and vulnerabilities in this important sector.

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.[6]

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[7]

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.

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

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

The semiconductor industry grew rapidly following the invention of the transistor. In 1957, the industry already 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.[8] 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.

According to the SIA 2021 Factbook, semiconductor sales were US$440.4 billion worldwide in 2020, up from US$204.4 billion in 2000. In 2021, global semiconductor industry sales reached US$555.9 billion worldwide – an all-

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

time high — with the year-on-year growth rate of 26.2%.[9] The U.S. had a 47% market share in 2020, South Korea had 20%, the EU and Japan each had 10%, Taiwan had 7%, and China had 5%. However, a significant portion of the U.S. 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.[10] All three of these companies rely heavily on Taiwan foundries to produce their chips.

Other important U.S. 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 3nm.[11] [12] 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.

Taiwan's Rise as a Global Semiconductor Leader

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.

In the third quarter of 2021, Taiwan was the largest semiconductor equipment market in the world, thanks to purchases of machinery and other equipment totaling US$7.33 billion — a 54% increase over Q3, 2020.[13] 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.

As noted, TSMC is the driver for the semiconductor industry on the island. The company is the world's largest foundry chipmaker, with a global capacity of about 13 million 12-inch equivalent wafers per year.[14] TSMC uses a wide range of technologies — from old school 2 microns to state-of-the-art 3 nm – and also leads on development of future technologies.[15] 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.

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[9] "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/

[10] "Gartner Says Worldwide Semiconductor Revenue Grew 25.1% in 2021, Exceeding $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

[11] 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/

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

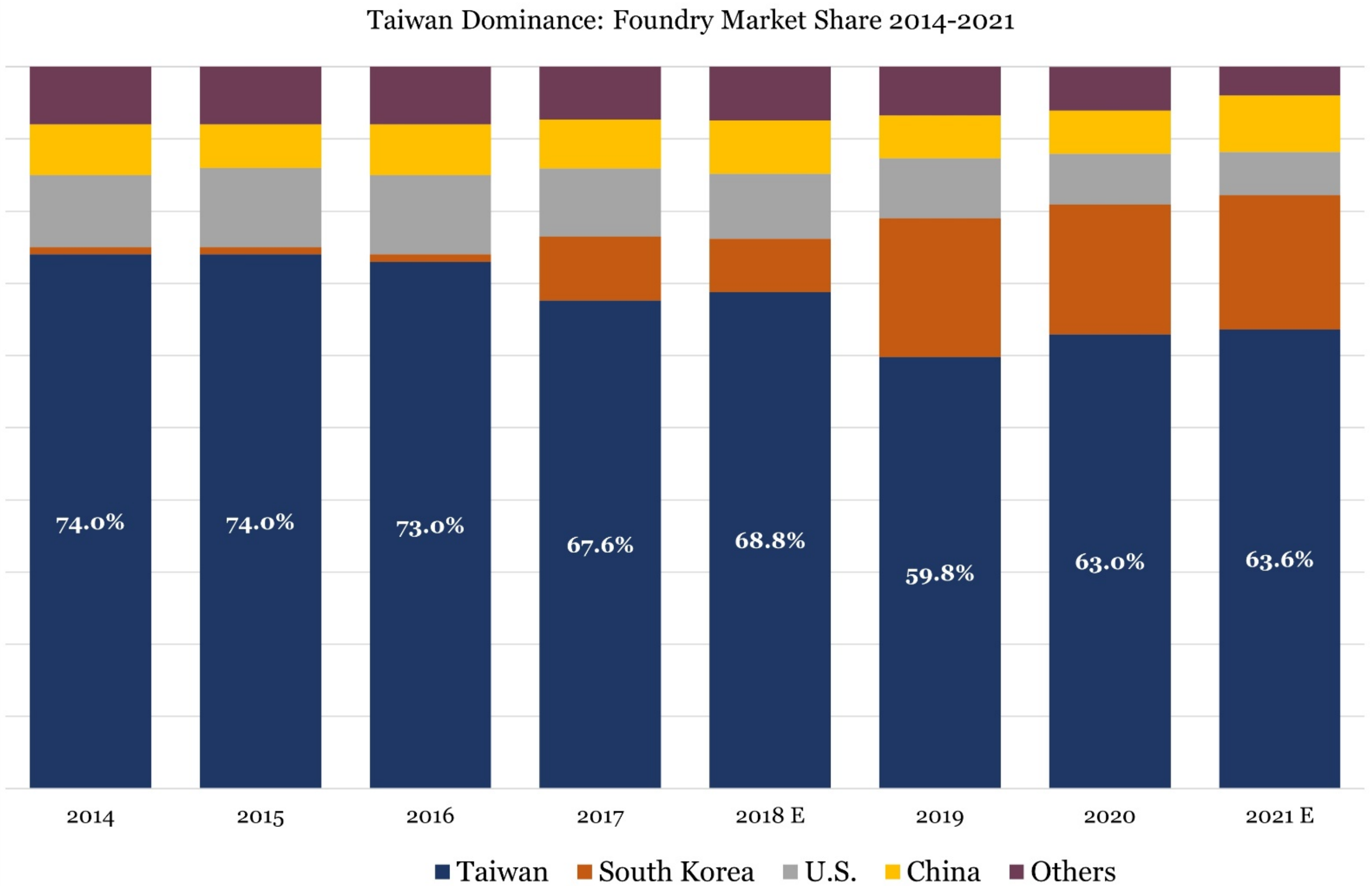
[13] "Global Semiconductor Equipment Billings Jump 38% Year-Over-Year in Q3 2021, Log Fifth Straight Quarterly Record, SEMI Reports," *SEMI Worldwide Semiconductor Equipment Market Statistics (WWSEMS) Report*, December 1, 2021, https://www.semi.org/en/news-media-press/semi-press-releases/global-semiconductor-equipment-billings-jump-38%25-year-over-year-in-Q3-2021-log-fifth-straight-quarterly-record-semi-reports

[14] A wafer is a thin slice of semiconductor material that serves as a base for ICs. Semiconductor plants are often described by the diameter of wafers they produce, with larger wafers making for more cost-effective production. "Semiconductor Wafer – Overview and Facts," *AnySilicon*, June 16, 2015, https://anysilicon.com/semiconductor-wafer/

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

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, United Microelectronics Corporation (UMC), Powerchip Technology Corporation, and Vanguard International Semiconductor Corporation — is estimated at just under 64% in 2021, which is still below its historical highs as shown in Figure 2.

Figure 2: Taiwan Dominance — Foundry Market Share 2014-2021



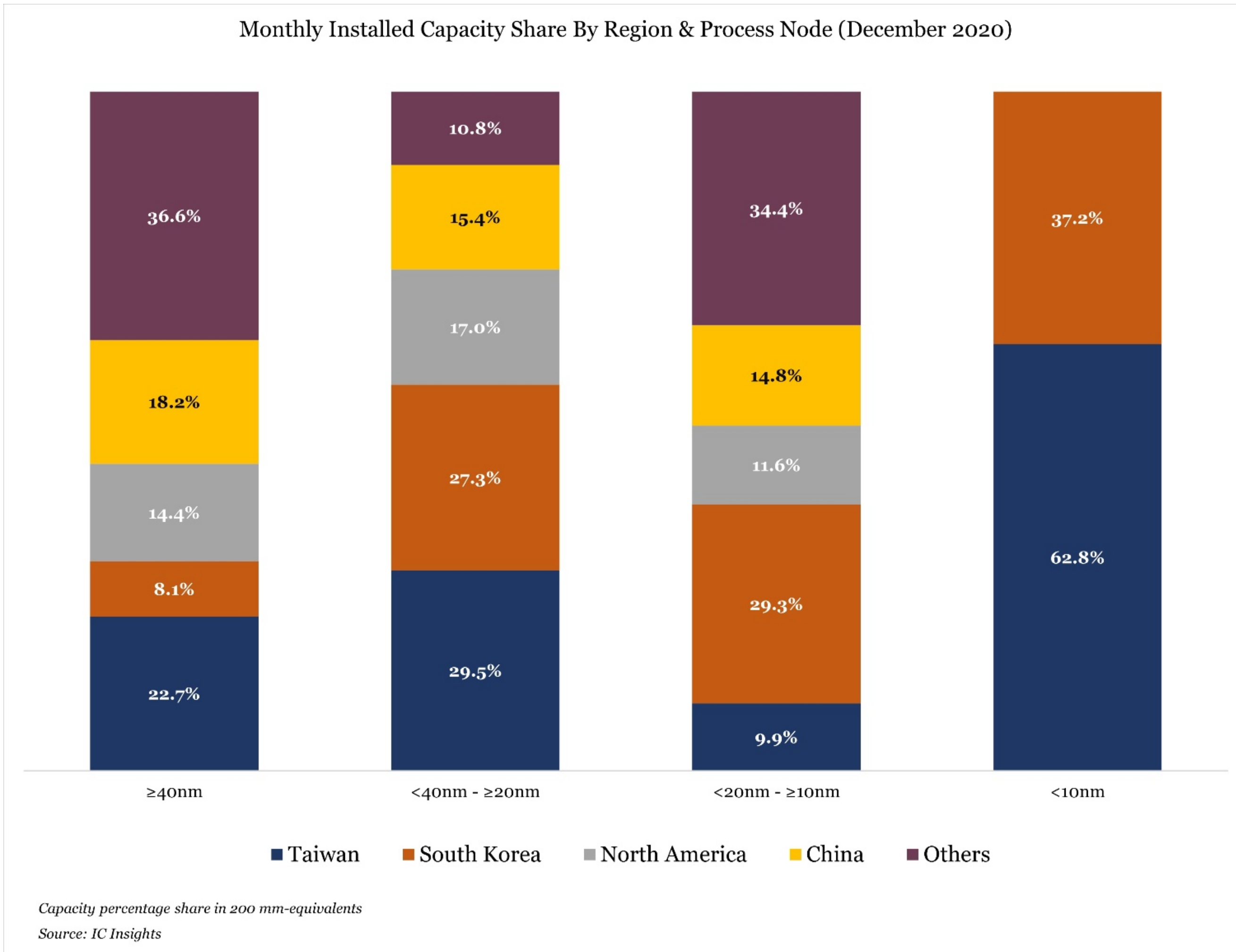
Taiwan foundry companies include TSMC, UMC, Powerchip, and Vanguard.

2014-2016 data from IC Insights
2017-2021 data from TrendForce
2018 E = Estimate (Based on 1H)
2021 E = Estimate (Based on Q1, Q2, Q3, Q4)

As of December 2020, Taiwan also held 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.[16] See Figure 3 for the percentage share of total monthly installed capacity, in 200 mm-equivalents, by geographic region and by process node.

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

Figure 3: Monthly Installed Capacity Share by Region & Process Node



Finally, Taiwan is also a leader when it comes to semiconductor assembly and testing, a market segment consisting 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 over 45% of the OSAT market.[17]

The U.S. government recognizes the importance of Taiwan to the semiconductor industry. In January 2020, the United States government urged TSMC to produce leading-edge chips in the U.S. to ensure a supply of high-security components manufactured on U.S. soil.[18] 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.[19]

[17] "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/

[18] 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

[19] 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

However, 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. Construction on the fab started in 2021, and it is scheduled to start production in 2024. While this represents a single digit percentage of TSMC's overall global footprint, with its primary operations still in Taiwan, this is a good first step.

The TSMC fab is a major foreign investment in the U.S., given its price tag of approximately US$12 billion when announced in 2020, and it will be one of the most technically advanced facilities in the country. The new fab would create approximately 1,800-2,000 local jobs, and would be a boon to the semiconductor industry ecosystem in Arizona.[20] This is particularly true if the TSMC investment draws 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.[21] The TSMC announcement in 2020 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.

China still relies on other countries for advanced chips, with a strong dependence on imports from Taiwan, despite 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 dependent on Taiwan semiconductors, thus introducing the risk of severe damage to Chinese companies as well, in the eventuality that the supply chain should be compromised.

At the same time, the semiconductor industries on both sides of the Taiwan Strait are intertwined, and Taiwan has 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.[22] 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.[23] In fact, the company's total revenue in 2021 grew 18.5% year-on-year.[24]

[20] Vanek, Corina, "Major semiconductor maker zeroing in on Phoenix site for huge factory," *Phoenix Business Journal*, October 20, 2020, https://www.bizjournals.com/phoenix/news/2020/10/20/semiconductor-manufacturer-zeroing-in-on-phoenix.html

[21] 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/

[22] 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/

[23] 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.

[24] "Financial Results -2021 Monthly Revenue," *TSMC*, March 15, 2022, https://investor.tsmc.com/english/monthly-revenue/2021

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.*"[25] 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 expenditures.

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 US$150 million each, with newer and more advanced tools at well above US$340 million each.[26] Building and equipping a state-of-the-art wafer fab of standard capacity requires an investment of approximately US$5-20 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.

[25] 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/

[26] Sterling, Toby, "Intel orders ASML system for well over $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.

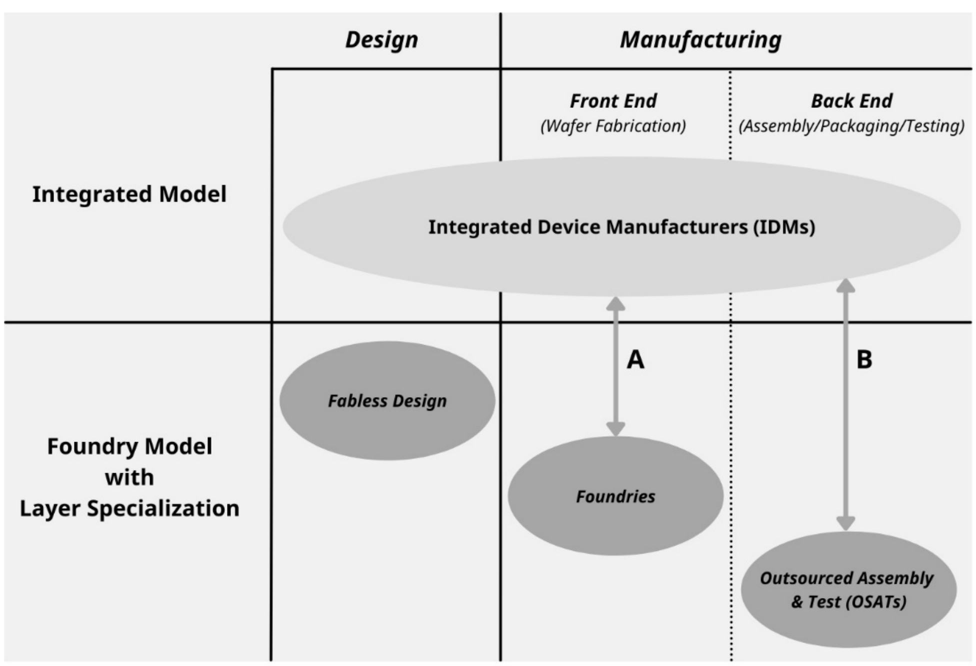
As indicated above, the semiconductor supply chain has a highly specialized upstream support ecosystem. The Design step is supported by Electronic Design Automation (EDA) software and services, as well as by reusable components designs (called IP blocks) that have a defined interface and functionality. The Frontend and Backend steps are supported by the 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 4: Semiconductor Business Models



A: IDMs utilize foundries for some manufacturing
B: IDMs utilize OSATs for some assembly/packaging/testing

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 70% of global semiconductor sales as of 2019.[27]

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 are able to 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 33% in 2020.[28]

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, 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.[29]

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.[30] 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.

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.

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[27] Varas, Antonio, et al., "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/

[28] Alsop, Thomas, "Fabless/system company integrated circuit (IC) sales as share of total IC sales worldwide from 2002 to 2020," *Statista*, May 20, 2021, https://www.statista.com/statistics/1233607/fabless-ic-sales-share-total-ic-sales-worldwide/

[29] "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/

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

ASE (Taiwan), Amkor (U.S. headquartered with most manufacturing in Asia), JCET (China), and SPIL (Taiwan) are the four largest OSAT companies by revenue, and the sector experienced a 35% year over year increase in the second quarter of 2021.[31]

Geographic Distribution

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 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 2019: US-39%; South Korea-16%; Japan-14%; China-9%; Taiwan-9%; and Europe-10%.[32]

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.[33]

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 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, and contains about 100,000 parts provided by over 5,000 suppliers spread across the globe.

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

[31] "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/
[32] "2021 State of the U.S. Semiconductor Industry," op.cit.
[33] Ibid.

intensive R&D activities, while the bulk of manufacturing is now conducted in Asia.[34]

Many of the top universities in the world in terms of semiconductor manufacturing research are located 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 located 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. The U.S. has a 41% share in this market, Japan has a 32% share, and Europe has a 18% share (with much of the European share from ASML in the lithography space).

When it comes to wafer fabrication, four regions in Asia make up the bulk of the manufacturing capacity. The U.S. is down to a 12% share, while Taiwan is at 20%, South Korea at 19%, Japan at 17%, China at 16%, Europe at 9%, and other countries at 6%.[35] 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.[36] 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.[37]

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.[38] 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.

In contrast to Frontend operations, Backend operations are much less capital intensive, and a higher percent 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.

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

35 "World Fab Forecast (WFF)," op.cit.

36 "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

37 Varas, Antonio, Varadarajan, Raj, Goodrich, Jimmy, and Falan Yinug, "Government Incentives and US Competitiveness in Semiconductor Manufacturing," *Semiconductor Industry Association*, September, 2020, https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf

38 "World Fab Forecast (WFF)," op.cit.

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 are currently the world's 4th most traded product, ranking only behind crude oil, motor vehicles and parts, and refined oil.

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.[39]

The supply chain risk is clear across many sectors, including medical equipment, pharmaceuticals, and consumer goods, but it also holds true for the semiconductor sector. Semiconductors are of critical importance because they are the main component of modern electronics, and have therefore helped drive technological innovation and other advancements. A disruption of the global supply chain for semiconductor chips and other related devices would have serious repercussions for U.S. businesses and consumers, negatively impacting the U.S. and global economy, severely damaging the technology sector, and hampering innovation.

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.*" [40] He directed the heads of several agencies to produce a report identifying the risks associated with various supply chains, and to make policy recommendations to address these issues. 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.[41] 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

[39] "6 Strategies for a More Resilient Supply Chain," Gartner, Sarah Hippold, June 23, 2020, https://www.gartner.com/smarterwithgartner/6-strategies-for-a-more-resilient-supply-chain

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

[41] "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

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.[42] 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 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.[43]

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 in regard to 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.[44]

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.[45] [46] 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.[47] While China has made some progress on IP related enforcement, challenges persist across a number of 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 plead 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 May 2022. An earlier

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

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

44 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

45 "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

46 "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

47 "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

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.[48] Currently, only TSMC and Samsung can produce 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 have to 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. [49]

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 all of the numerous resources required to produce semiconductor devices. There 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 COVID-19 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.

<u>Silicon Wafers</u>

In 2021, global demand for silicon wafers for semiconductor applications reached 14.17 billion square inches, up 14% from the 12.41 billion square inches that was recorded in the previous year.[50] 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.

[48] "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
[49] "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
[50] "Silicon Shipment Statistics," *SEMI*, https://www.semi.org/en/products-services/market-data/materials/si-shipment-statistics

Moreover, the pandemic has added to the challenge faced by wafer manufacturers in expanding their facilities owing to the weakening financial situation.[51] Currently, 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 anticipated U.S.-based TSMC and Samsung facilities.

In 2011 a major earthquake 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 was 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 nanometers 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 disruption to a critical supplier of 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.

The global Semiconductor Manufacturing Equipment market was US$39.5 billion in 2020, and is projected to reach US$53.2 billion by 2027, at a compound annual growth rate (CAGR) of 3.9% during the forecast period 2021-2027. The EUV market is expected to increase from US$1.24 billion in 2017 to US$10.31 billion by 2023, at a CAGR of 28.16% during the forecast period.[52]

Materials

There are as many as 300 different materials needed to produce an advanced semiconductor device, 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 material market is projected to reach US$52.4 billion by 2026, from US$40.4 billion in 2019, at a CAGR of 3.3% during 2021-2026. Asia accounted for roughly 63% of the 2019 materials market, with Taiwan

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[51] 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

[52] "Semiconductor Manufacturing Equipment Market to Reach USD 53200 Million by 2027 at CAGR 3.9% - Valuates Reports," *CISION PR Newswire*, May 6, 2021, https://www.prnewswire.com/news-releases/semiconductor-manufacturing-equipment-market-to-reach-usd-53200-million-by-2027-at-cagr-3-9---valuates-reports-301285723.html.

a key market due to its extensive foundry business.[53]

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 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.[54]

The war in Ukraine is another very recent example of the potential impact of a geopolitical conflict on the semiconductor industry. Neon is a major component in the manufacturing of semiconductors, and Ukraine supplies 50% of the world's neon gas. Roughly 250 tons of neon are produced annually by two Ukrainian companies.[55] Current neon supplies are reported to last no more than three months, and production in Ukraine is not expected to start anytime soon — this materials supply issue is expected to exacerbate the chip shortage. [56]

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*."[57] 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.[58]

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.[59] 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

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53 "Semiconductor Manufacturing Equipment Market to Reach USD 53200 Million by 2027 at CAGR 3.9% - Valuates Reports," *CISION PR Newswire*, May 6, 2021, https://www.prnewswire.com/news-releases/semiconductor-manufacturing-equipment-market-to-reach-usd-53200-million-by-2027-at-cagr-3-9---valuates-reports-301285723.html.

54 "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

55 "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

56 "Commodities Shortage: Semiconductor &Automotive", *resilinc.com*, https://resource.resilinc.com/rs/863-OTG-034/images/Resilinc%20Special%20Report-Semiconductor%20Shortage%20and%20Impacts-Automotive%20Industry.pdf

57 "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

58 "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/*

59 "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

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 eye to water conservation efforts, and to implementing sustainable water resource management strategies.[60] 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 — in an effort to stop reserves from running dry.[61] 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.[62]

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.[63] The power needed for a new fab in 2022 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.[64]

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.

In another example, in December 2020 a power outage affected a memory fab located in Taiwan for just one hour, which took it offline for several days for restarts and caused 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.[65]

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.

[60] 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/

[61] "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

[62] "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

[63] "8 Things You Should Know About Water & Semiconductors," op.cit.

[64] "Chandler commits $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/

[65] 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.[66] 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 in the section devoted to the current chip shortage below.

[66] "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

Taiwan may be ***the*** most critical link in the entire technology ecosystem. Contract manufacturers of semiconductors ("*foundries*," see the discussion on business models above) 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 produce chips at 5 nm. In 2019, Taiwan was estimated to account for approximately 92% of all semiconductor production at process nodes less than 10 nm.[67] 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 45% of the OSAT market.[68] 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 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, in particular given its complex political and diplomatic situation and existing tensions with its neighbor across the Taiwan Strait. China increased its pressure on Taiwan in 2021 and into 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 that 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.[69] 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.[70] 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.

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[67] Ezell, Stephen, "The Future of Taiwan: Semiconductors Alone Make the Island's Continued Freedom Crucial to the U.S.," *Discourse*, April 16, 2021, https://www.discoursemagazine.com/politics/2021/04/16/the-future-of-taiwan-semiconductors-alone-make-the-islands-continued-freedom-crucial-to-the-u-s/

[68] "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/

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

[70] 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.

Implications of Supply Chain Disruption Involving Taiwan

Given this important role of Taiwan in the global semiconductor supply chain, almost any disruption involving Taiwan will impact the U.S. and the rest of the world.

U.S. Economy and Capital Markets

As discussed in the earlier parts of this report, there are numerous semiconductor connections between the U.S. and Taiwan. These connections include the purchase of completed semiconductor devices from the other country (e.g. Taiwan purchases from U.S. manufacturers such as Intel and Micron) and foundry services provided by the other country (mainly U.S. fabless companies such as Qualcomm and Nvidia contracting with Taiwan foundries), along with interconnected networks among all facets of the semiconductor industry, including OSATs and other suppliers. According to the U.S. Census Bureau, in 2021 U.S. exports of semiconductors and related devices to Taiwan were US$5.11 billion, and imports from Taiwan were US$6.14 billion.[71] In its 2020 annual report to shareholders, TSMC disclosed that 62% of its annual revenue came from North America, with the comparable figures for UMC and Vanguard at 30% and 5%, respectively. Powerchip included North America in its "other" category, which together amounted to 11% of the company's overall revenue in 2020.[72]

As we are seeing from the current chip shortage, any disruptions to the semiconductor supply chain can negatively impact the U.S. economy. While to date there has not been a significant impact on U.S. capital markets, there has been a substantial impact on the price and availability of automobiles and other products containing a large number of semiconductors or ICs. This has led to inflationary trends that very well may have an impact on the economy and ultimately on U.S. capital markets.

U.S. Defense and National Security

Advanced semiconductors 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 has identified 81 accredited suppliers.[73] 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 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. While the Trusted Foundry Program may be sufficient to satisfy the needs for exotic, low volume custom chips designed by the U.S. military, it is not sufficient to cover all of 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

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71 "U.S. Import and Export Merchandise trade statistics for NAICS Code 334413," *USA Trade Online*, https://usatrade.census.gov/

72 "2020 Annual Report," *TSMC*, https://investor.tsmc.com/english/annual-reports; "2020 Annual Report," *UMC*, https://www.umc.com/en/Download/annual_reports; "2020 Annual Report," VIS, https://media-vis.todayir.com/20210518100431357633284_en.pdf;"Q4, 2020 Consolidated Financial Statements," PSMC, https://www.powerchip.com/investor_en.html

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

year.[74] Instead, many of the general-purpose semiconductors needed for advanced weapons 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.[75] 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 a number of sectors where potential disruptions could have a destabilizing impact on society, designating them as critical infrastructure.[76] 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. Thankfully, the United States has a very strong domestic compound semiconductor sector and is a world leader in the industry. It 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%).[77] 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

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74 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

75 Leading Edge Update Newsletter, *TSMC Government Affairs*, May 10, 2022

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

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

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 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 TSMC's forthcoming Arizona fab is estimated to cost roughly the same as the U.S. Navy's Ford-class aircraft carrier. While the recently passed CHIPS Act allocated US$52 billion for domestic semiconductor R&D and manufacturing in the U.S., TSMC alone intends to spend US$100 billion over the next three years.[78]

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.

[78] "TSMC to Spend $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

Current Status of the Semiconductor Supply Chain

Chip Shortage

As discussed above, changes in demand can be disruptive to the semiconductor supply chain. Early in the COVID 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 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 due to its use in the mass production of COVID-19 vaccine vials. The silicon needed to make the vials is the same as the silicon used to manufacture chips.[79]

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.[80]

Given that the lead time for computer chips is generally around three months at the best of times, and that labor and supply shortages continue as the pandemic lingers, the chip shortage is likely to continue for quite some time.[81] Intel CEO Pat Gelsinger recently stated: "*We're in the worst of it now; every quarter next year, we'll get incrementally better, but they're not going to have supply-demand balance until 2023.*" [82]

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

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79 "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

80 "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

81 "Chip shortage expected to cost auto industry $210 billion in revenue in 2021," CNBC.com, Sept. 23, 2021, https://www.cnbc.com/2021/09/23/chip-shortage-expected-to-cost-auto-industry-210-billion-in-2021.html

82 "Intel CEO warns chip shortage won't end until at least 2023, as laptop sales get hit by supply issues," theverge.com, C. Gartenberg, Oct 21, 2021, https://www.theverge.com/2021/10/21/22739192/intel-chip-shortage-q3-2021-earning-laptop-revenue

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 current 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 hopefully forthcoming 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.[83] 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 current chip shortage is 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 2023-2025 timeframe, when the pandemic-related demand pressures may have already dissipated. In addition, past boom-and-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.[84]

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 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.

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 time 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, in an attempt to produce up to 70% of the chips it needs by 2025.[85] It is clear that 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

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[83] 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/

[84] 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

[85] "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

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.

As a first step, bipartisan legislation called the CHIPS for America Act was enacted in 2021. It authorizes investments in domestic chip manufacturing incentives and research initiatives. Congress is also considering legislation called the FABS Act that would establish a semiconductor investment tax credit to help strengthen the entire semiconductor ecosystem.

On June 8, 2021, the U.S. Senate passed the U.S. Innovation and Competition Act (S.1260), which includes US$52 billion in investments to support the domestic semiconductor research, design, and manufacturing provisions in the CHIPS Act. On February 4, 2022, the U.S. House of Representatives also passed the America COMPETES Act (H.R.4521) which similarly includes US$52 billion in CHIPS Act investments. Reconciliation of these bills are in progress, and passage of joint competitiveness legislation containing CHIPS Act investments could then be signed into law by President Biden.

The Semiconductor Industry Association succinctly summarized the stakes for the United States:

> *"By funding the CHIPS Act and expanding and enacting the FABS Act, leaders in Washington can usher in a historic resurgence of chip manufacturing in America, strengthen our country's most critical industries, boost domestic chip research and design, and help ensure the U.S. leads in the crucial, chip-enabled technologies that will define America's strength for decades to come."*[86]

[86] "CHIPS for America Act & FABS Act: Invest in Domestic Semiconductor Manufacturing, Research & Design," *Semiconductor Industry Association*, https://www.semiconductors.org/chips/

Conclusions and Next Steps

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. 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 is able to 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 and UMC) 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 currently have the ability to produce chips at this level of sophistication. The U.S. must do everything it can to maintain its leadership position in the industry, and this includes ensuring that Taiwan remains a close ally.

The CHIPS for America Act is a positive first step in supporting the semiconductor industry, and the funding it will provide is also an incentive for companies such as TSMC, Samsung, and Intel to build leading-edge wafer fabrication facilities on U.S. soil. However, given the importance of this industry, more will need to be done in encouraging further U.S. growth on semiconductors. The proposed FABS Act should be expanded to include tax credits on expenditures for both manufacturing and design, to help strengthen the U.S. position.

This initial report is intended to begin the discussion on these important matters, and to provide an outline of some of the issues we will cover extensively during this research project, which will continue during the remainder of 2022.

The final report will build upon this initial report, and will further address a set of nine questions that fall into four main categories: 1) sources of disruptions in the semiconductor supply chain and the implications of such disruptions to the supply chain connecting Taiwan and the U.S.; 2) the impact of disruptions in the Taiwan-U.S. semiconductor supply chain on the U.S. economy and financial markets; 3) the impact of disruptions in the Taiwan-U.S. semiconductor supply chain on U.S. national security; and 4) how the U.S.-Taiwan semiconductor supply chain can become more resilient and be utilized to provide a pressure point to influence China's behavior. We will attempt to answer these questions by concluding a thorough literature review and by conducting extensive interviews with key industry and government leaders both in the U.S. and Taiwan.

The final report is intended to be an educational resource for the D.C.-based policy community, raising awareness of potential semiconductor supply chain disruptions, while also making recommendations for ways to address both existing and future vulnerabilities. It will be widely disseminated and used to educate the policy community on this vital sector.

The final report will also provide U.S. policymakers with insights into U.S.-Taiwan relations, into Taiwan's technological advancements, and into the island's importance both to the U.S. economy and to the global technology industry. It will also offer deeper insights that are likely to play into existing U.S. concerns of the potential consequences of China's growing military and economic assertiveness in the Taiwan Strait.

The report will address what these dynamics mean for medium to long term U.S. strategy in the Indo-Pacific region, and will provide recommendations for optimizing policy outcomes.

The Project 2049 Institute and the US-Taiwan Business Council look forward to working with the broader semiconductor community on this project, and welcome outreach by community members who are interested in contributing their thoughts to project staff and stakeholders.