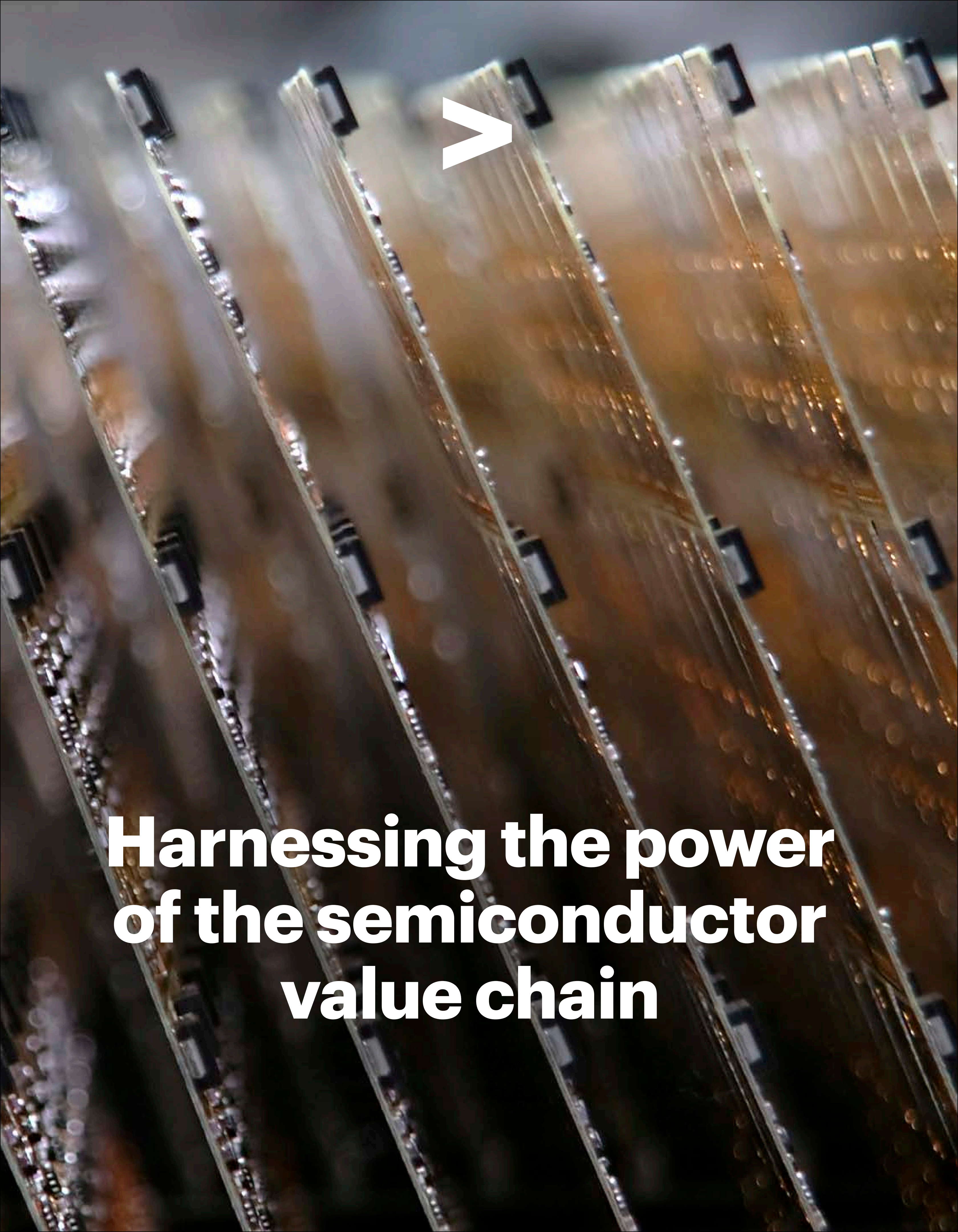


Harnessing the power of the semiconductor value chain

Table of contents

Executive summary

The semiconductor industry is more than 70 years old and ubiquitous in our daily lives. However, due to recent events, the public is now more keenly aware than ever of this industry and the corresponding ramifications of disruption.

COVID-19 spikes, natural disasters, power outage induced facility shutdowns, geopolitical conflicts, and accelerated digital transformation have all combined to disrupt the semiconductor industry, leaving no company immune to the effects of the ongoing global chip shortage. In particular, the impact to the automotive sector captivated the world's attention. Carmakers radically underestimated demand that led to a significant reduction in orders when the COVID-19 pandemic hit. Now, auto manufacturers are facing double- to triple-digit revenue losses, shutting down factories due to semiconductor shortages, even while demand for cars remains high.

Beyond automotive, nearly 200 additional downstream sectors—ranging from high tech gaming console vendors to household appliance producers to ready-mix concrete manufacturers and textile product mills—have also struggled to secure enough chips to meet consumer demand due to the silicon shortage. Companies have suffered nontrivial revenue hits as consumers wait impatiently for Teslas, Ford Fiestas, iPads, PlayStations, wine coolers, dog-washing booths, toaster ovens, dryers, and countless other products (see Exhibit 1). Some sectors have rebounded, while many others have relapsed due to lockdowns aimed at preventing the spread of contagious COVID-19 variants.

Key theses

1. No one country or company can achieve end-to-end semiconductor independence, at least not within the next decade. Domestic / onshore foundry capacity cannot be attained in the near-term.

2. Advancement and priority in design is imperative to continued innovation not only in the semiconductor industry, but also to the tech landscape at large.

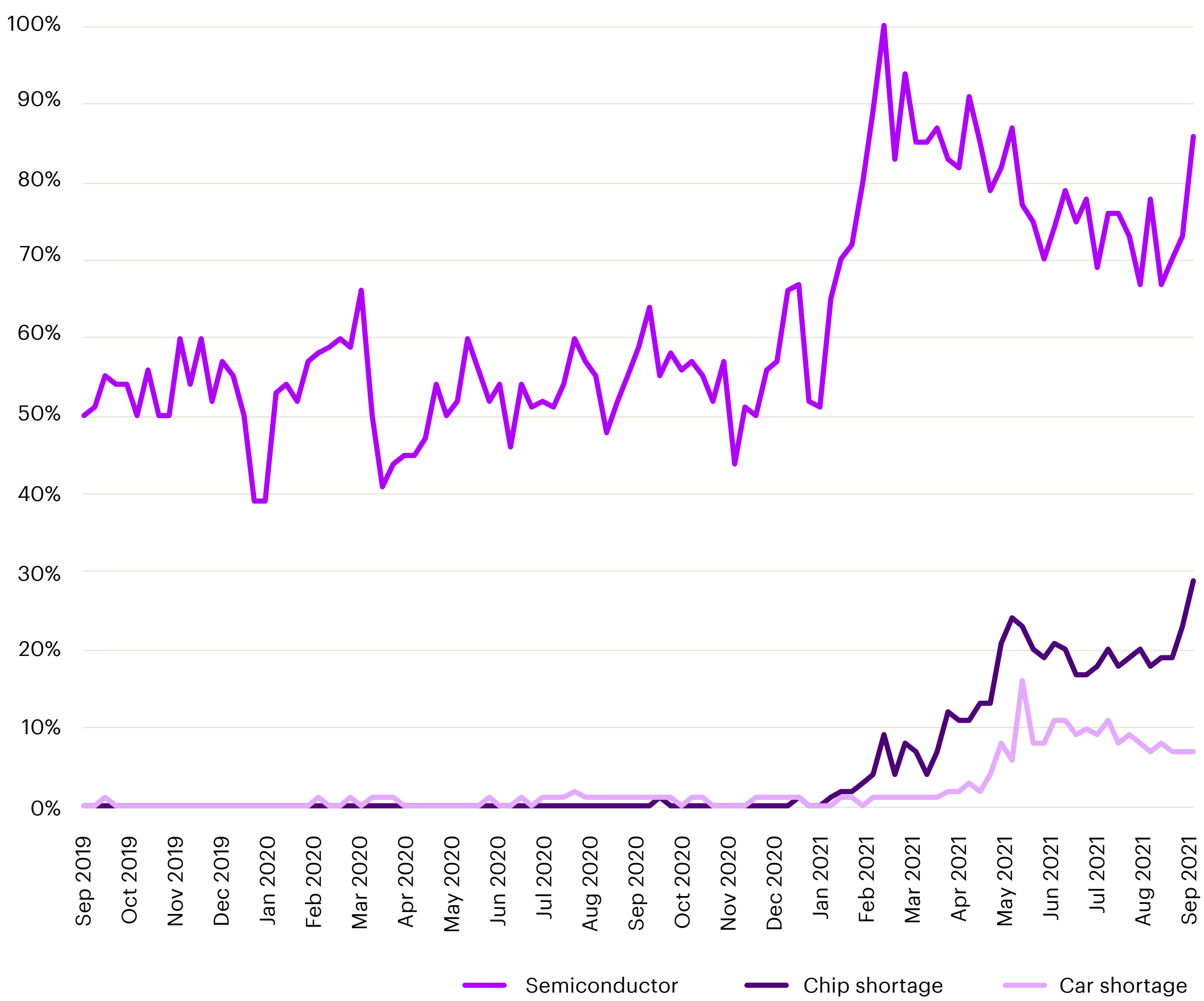
3. COVID-19 has strained the semi value chain and exacerbated the ongoing global chip shortage and escalating geopolitical tensions. However, the fragility existed long before the pandemic.

Exhibit 1: Highest-rated semiconductor-related search terms (Source: Google Search Trends Analytics; Note: Y-axis reflects a normalized measure of search volume for a given search over a defined period)

Subset of highest-rated semiconductor-related Google Search terms

WHY IS THERE A SEMICONDUCTOR SHORTAGE
WHEN WILL CHIP SHORTAGE END
SEMICONDUCTOR CHIP SHORTAGE
COMPUTER CHIP SHORTAGE NEW CAR CHIP SHORTAGE
AUTO CHIP SHORTAGE AUTO SHORTAGE
GLOBAL CHIP SHORTAGE CHIP SHORTAGE CARS

Semiconductor-related Google search trends



While COVID-19 has certainly stretched the semiconductor value chain, it is important to recognize that **its fragility emerged long before the pandemic**. Semiconductor manufacturing has become incredibly complex and the effort it takes to get electronics in front of the end customer at a reasonable price point is very challenging. **Each end application**—be it refrigerators or tractors—**hinges on hundreds to thousands of meticulously planned, designed, and manufactured semiconductor chips**. While each of these chips may come from a different company, they are all part of a larger solution. When supply of one singular chip is at risk, production of the entire end application is subject to delay.

No one company can execute across the end-to-end semiconductor value chain. Looking back at the history of the industry, however, it was largely consolidated through the 1970s. The landscape was defined by a subset of vertically integrated companies that focused on software, hardware, equipment, and manufacturing. This changed with the development of the fabless/foundry model in the 1980s – 1990s, a key inflection point in the business model and in the speed of innovation in the industry. As pure-play foundries pooled demand from multiple companies looking to outsource capital intensive manufacturing, they significantly lowered barriers to entry, enabling new fabless entrants to specialize almost exclusively on design. This specialization and focus were responsible for some of the most recognizable innovations in the last decade, including smartphones, IoT, and intelligence everywhere.

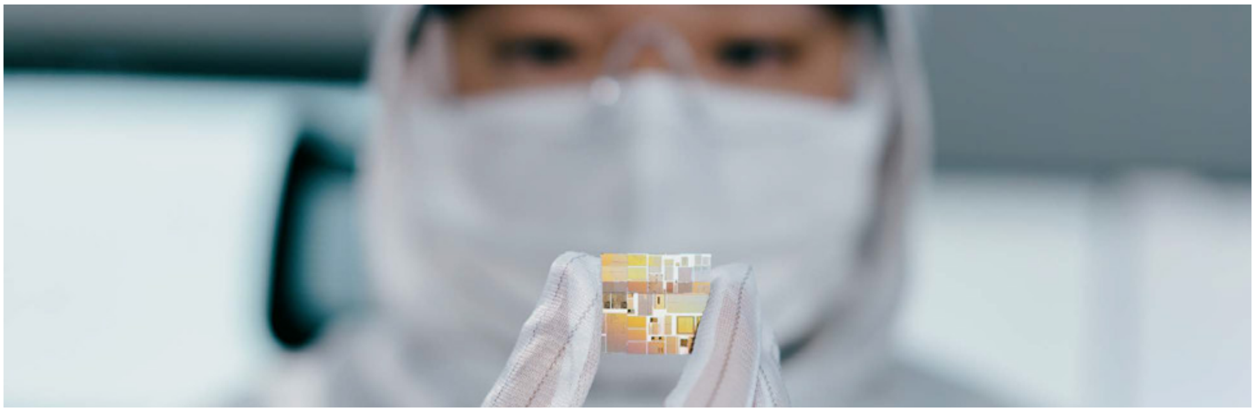
Today, the semiconductor value chain requires an immaculate level of cohesion across thousands of highly specialized suppliers around the world: IP and design from Silicon Valley, equipment from the US, Europe, and Japan, specialty chemicals and gases from Europe and East Asia, manufacturing outputs from East Asia, and packaging, assembly, and testing from Southeast Asia. This geographic dispersal complicates the development and manufacturing lifecycle of a chip. **However, it is precisely this global diversification of specialty talent, R&D and manufacturing facilities that fuels technological advancement in the industry**. To meet the rising demands of intelligent devices, edge computing, high-performance compute workloads, and 5G wireless infrastructure, increasingly complex chip designs are required to unlock gains in power, performance, and functionality. With this rise in complexity comes an even greater need for interlock and cross-border flow of talent, expertise, IP, materials, and equipment. If trade flows are obstructed, players along the entire value chain stand to lose in terms of their ability to meet customer demand for products that are so integral to the modern global economy.

Global Attention on the Semiconductor Industry

It's not just consumers that have become aware of the semiconductor industry, global governments also recognize the value of this industry to their regions. **Many countries are enacting policies to strengthen their own domestic semiconductor resilience**. As an example, the Chinese government introduced its Made in China 2025 initiative to gain chip independence. China produces 70% of chips it consumes, given that China accounts for roughly 60% of the global demand for semiconductors, but only manufactures 13% of the global supply.[1] The US is also placing focus on this industry, exploring the feasibility of passing the CHIPS for America Act, which would grant $52B in federal investments for domestic semiconductor R&D and manufacturing. Likewise, the EU has proposed the European Chips Act to strengthen the bloc's own self-sufficiency, particularly in capturing market share in design, increasing chipmaking capacity in Europe, and strengthening international cooperation through supply chain diversification. And in other parts of the world, South Korea's government is introducing tax deductions for semiconductor R&D and facilities, while Japan's government is earmarking $4.5B+ to bolster semiconductor supply chain resiliency.

While these efforts have largely been on bolstering domestic manufacturing capability, they do not guarantee that the US—or any country, for that matter—will retain its position in the semiconductor value chain. US-led advancements in chip design, IP, R&D, and equipment have served as the springboard for most modern innovation. However, over the past four decades, America's leadership in semiconductors has not been defined by its ability to source or manufacture locally, but by its stregnths in complex chip design and the ability to industrialize them by collaborating with ecosystem and manufacturing partners. Fabs are only able to manufacture chips that power cutting-edge applications such as ADAS, 5G/6G, and precision medicine because of advancements in design that come from homegrown fabless and EDA players.

This is not to undermine the benefits of additional onshore fabs, because investment in domestic fab capacity is sure to yield marked advantages for any economy. It can drive growth in highly skilled jobs, strengthen national security, and improve resilience in the case of future supply chain disruptions.



To achieve these objectives, this report is structured into five sections:

1. **Section 1** establishes the ubiquity of semiconductors and the complexities that caused supply chain vulnerabilities long before the COVID-19 pandemic

2. **Section 2** offers a historical view of the semiconductor industry, a detailed breakdown of the value chain, and current macroeconomic trends that define the sector

3. **Section 3** outlines the global interdependence of demand for semiconductors by product, geography and end-vertical (e.g., automotive, industrial)

4. **Section 4** discusses economic vulnerabilities due to the chip shortage by industry, the interplay of cost, quality, and speed, and a nuanced view of costs involved with building a fab

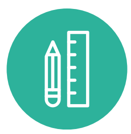
5. **Section 5** proposes recommendations that strengthen the resiliency of the global semiconductor ecosystem and lead with design to ensure continued innovation across a global semiconductor value chain

IP Protection

R&D Investment

Business Conditions

STEM Education



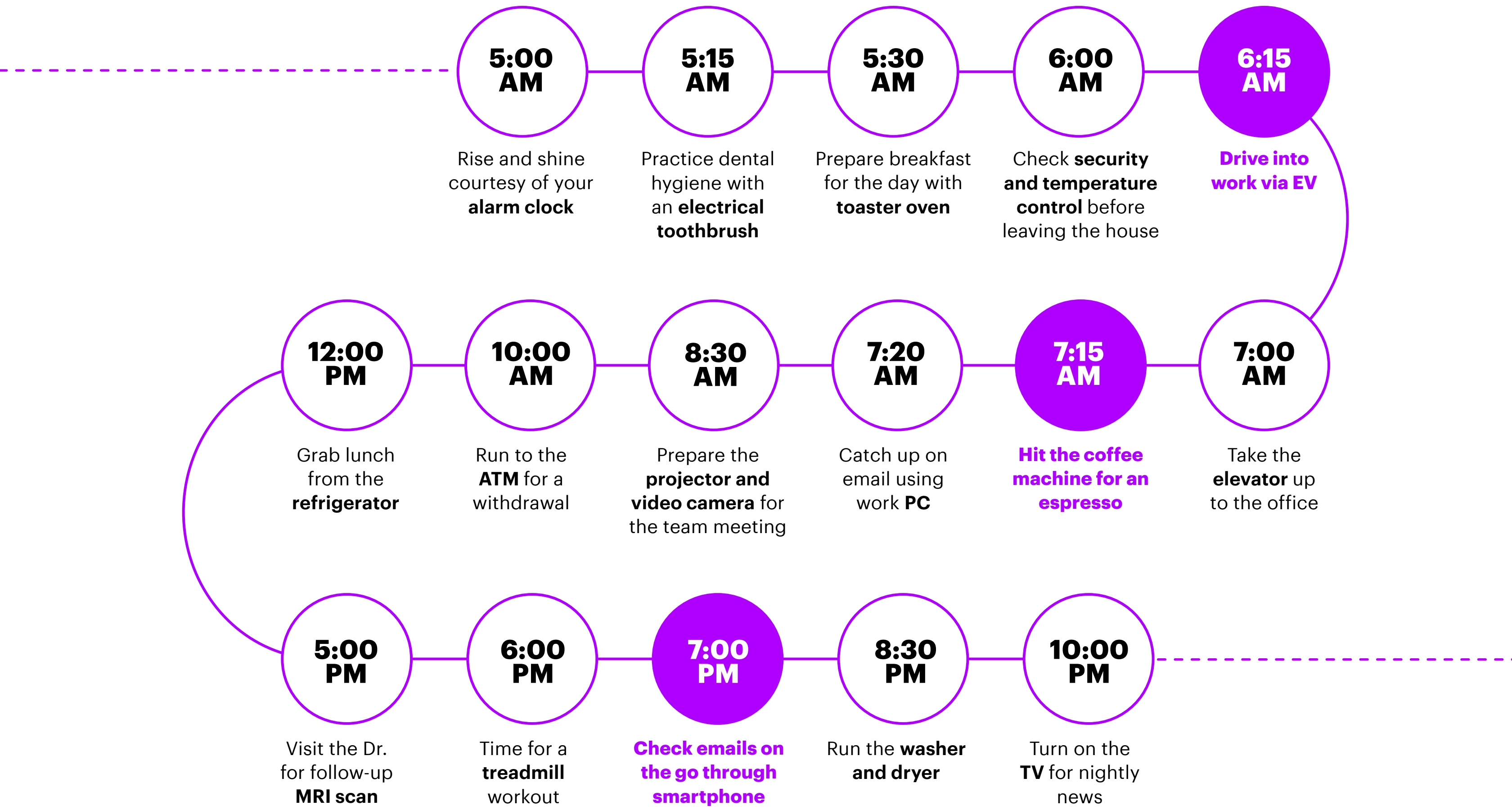
1

Introduction

What are semiconductors?

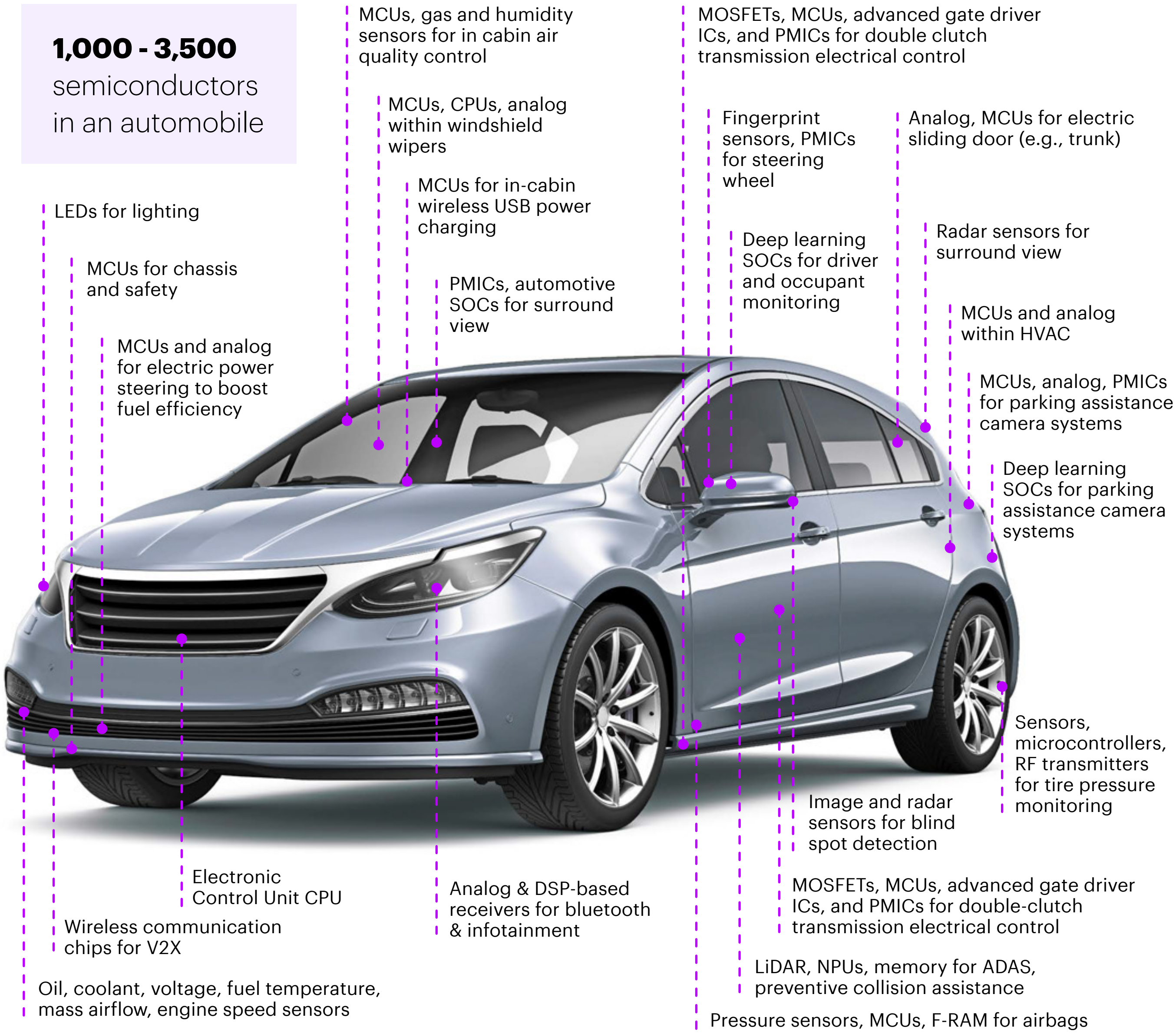
Semiconductor devices, also known as "chips", are the foundation of all modern electronics. A semiconductor is a material, typically silicon, whose ability to conduct electricity falls between a conductor (like copper) and an insulator (like glass). Its electrical properties can be changed by adding impurities, or by the application of electric fields, light or heat. Electronic components such as integrated circuits or ICs are a set of complex, minute electronic circuits integrated into a piece of silicon (hence, "chip"). These chips consist of thousands to billions of active and passive circuitry such as transistors, that control the flow of electricity for amplification, switching, storing, and mathematical operations. Importantly, they are readily manufacturable and economical at scale. Chips serve as the basis for all our modern technologies. They are our physical connection to the digital world, integral to the electronics that enable our daily existence and fuel cutting-edge technological advances in computing, wireless communications (5G), Internet of Things (IoT), quantum computing, and beyond (see Exhibit 2).

Exhibit 2: Semiconductors in everyday life

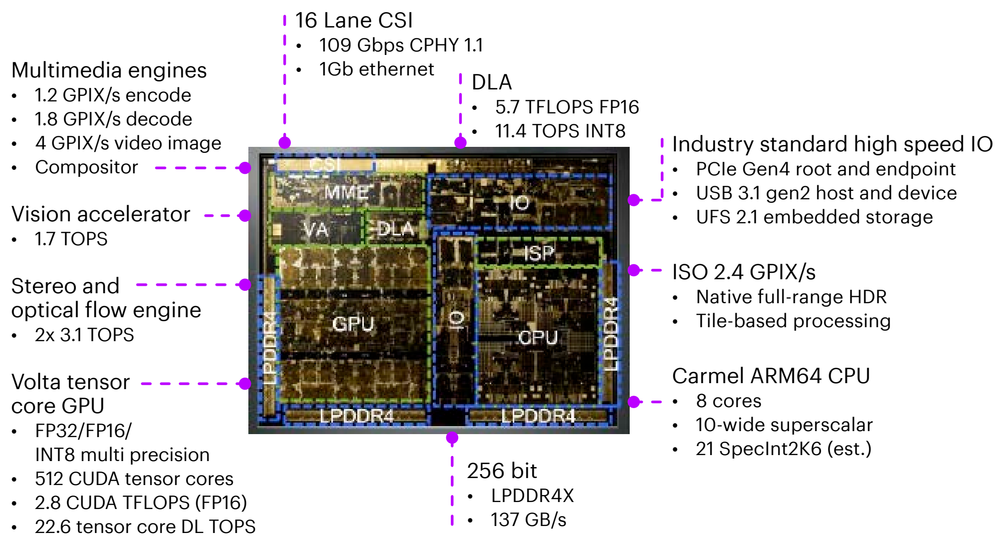


In the past, semiconductor growth was linked to PC and mobile growth, but today semiconductors are seen in every industry in the modern global economy as mission critical components for both in-flight and anticipated technological breakthroughs.

1,000 - 3,500 semiconductors in an automobile



Block diagram of a sample chip



10+ semiconductors in a coffee machine

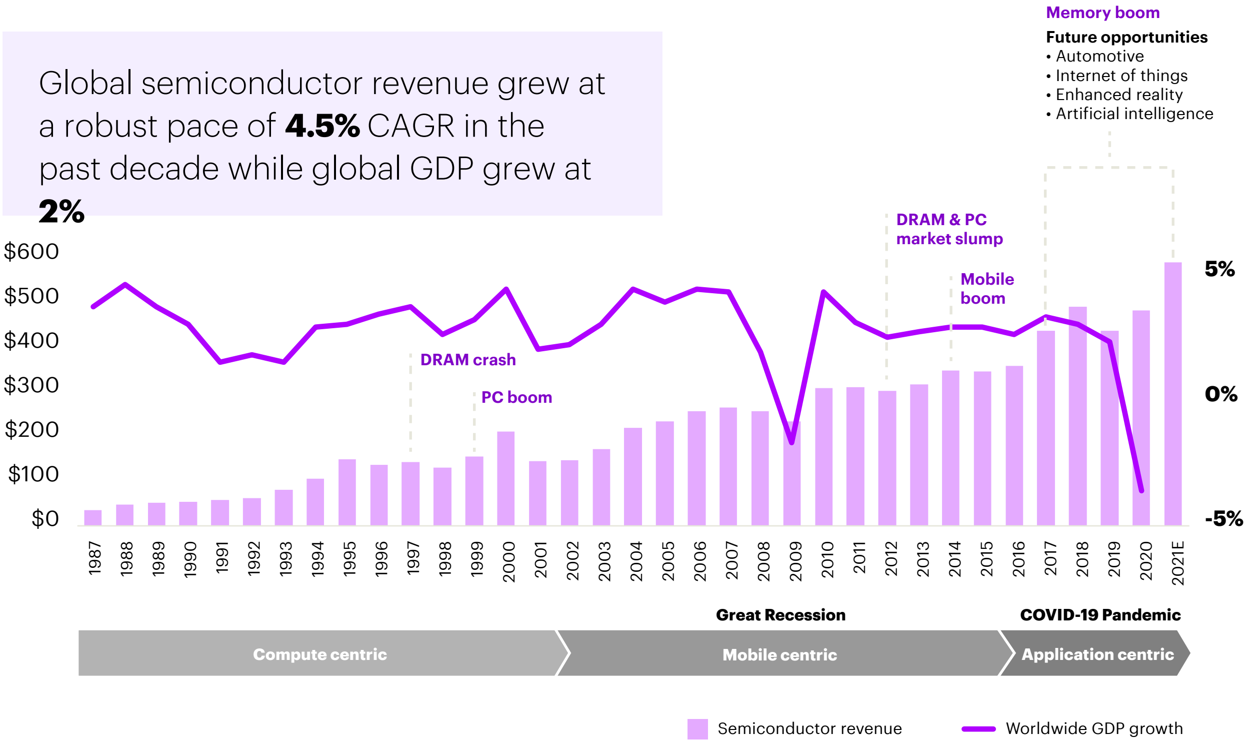
~169 semiconductors in a smartphone

The semiconductor industry has experienced remarkable growth

Over the past three decades, the semiconductor industry has experienced rapid growth to meet technological demands from changing consumer preferences and transformative technology inventions. The proliferation of PCs and rise of the internet drove the growth in the 1990s and 2000s. In 1994, global semiconductor sales surpassed $100B for the first time, followed closely by the $200B milestone in 2000.

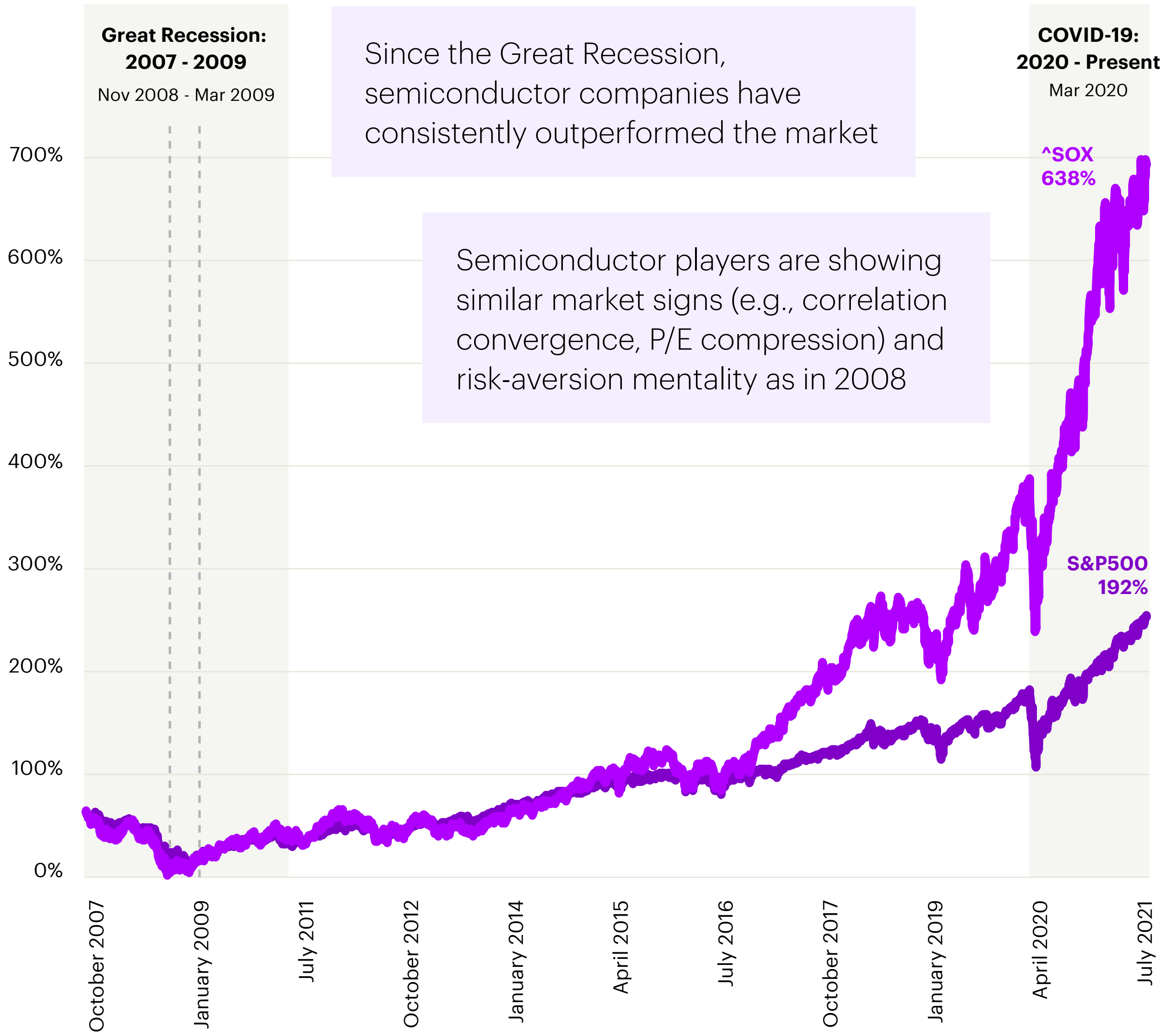
In the past decade, the semiconductor market grew at a robust 4.5% compound annual growth rate, driven by the invention and mass use of smartphones and other handheld devices. The industry reached $300B in 2011, spurred by global demand for smartphones such as Apple's iPhone. In 2017, the industry saw a 22% year-over-year revenue growth, blowing past the $400B milestone, driven by increased prices due to supply constraints and increased demand for memory chips.[2] More recently, advancements in key technological trends such as hyperscale cloud computing, Artificial Intelligence (AI), Internet of Things (IoT), and automotive Advanced Driver Assistance Systems (ADAS) have continued the growth trend—even as traditional uses for semiconductors continued to exist in high demand. Since its inception, the semiconductor industry has showed surprising resiliency, bouncing back from major global economic downturns, and outperforming global GDP growth for each of the past 3 decades. Moving forward, the industry forecast through 2025 remains promising with a 7.4% compound annual growth rate supported by forecasted increased capacity, stronger prices, and recovering demand.

Exhibit 3: Semiconductor revenue against global GDP growth



For shareholders, growth in the semiconductor industry has directly translated to higher market returns. Since the Great Recession, semiconductor companies have consistently outperformed the market.

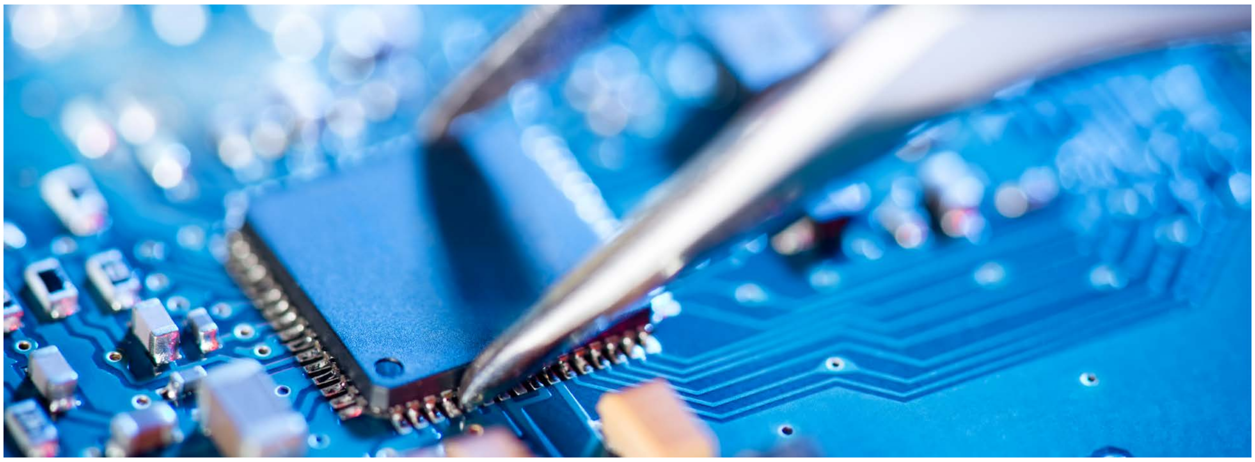
Exhibit 4: Semiconductor market return



However, while semiconductor chips have transformed the way people live, work and play, even the speed of innovation in the industry cannot meet customer demand. Exogenous factors such as disruptions in the global supply chain have snowballed into the current global chip shortage. While companies are rushing to meet demand, prices for goods dependent on semiconductor chips have and will continue to rise.

Supply chain vulnerability pre-dates the 2020 COVID-19 pandemic

COVID-19 has been an aggravator of the current global chip shortage, but not the catalyst. Disruptions caused by prior earthquakes, fires, floods, and droughts are testament to the inherent fragility in the semiconductor supply chain. Thus, today's record demand for computers and laptops as a result of work and study from home mandates, a rise in demand for medical devices, and the spread of new 5G mobile networks have only compounded the ongoing strain to the semiconductor supply chain.[3] It is these cascading factors that have brought the chip shortage to the forefront of the worldwide economy. However, without addressing the underlying vulnerabilities, supply constraints will continue to persist, beyond the "end" of the pandemic. There is no magic wand to end the chip shortage, but there is significant room to address this issue if we act now.



The semiconductor industry is rife with complexity

To understand the challenges in addressing a chip shortage, it is important to look at the entire industry—not just manufacturing and supply chain. The global nature of the semiconductor value chain is a direct result of the complexity of this industry's products. Indeed, global collaboration is vital for a single chip's success, requiring hundreds of thousands of people with specialized knowledge across a myriad of industries and regions.

With this understanding comes an appreciation for what it takes to put low-cost electronics in front of both consumers and the industry. Seismic changes in the global economic environment surrounding this industry unleashes an additional layer of complexity on an already complex business and must be done thoughtfully with an informed perspective.

2

How it started—the evolution & current state of the industry

History

The invention of the transistor by Shockley, Bardeen, and Brattain in 1947 forever changed the course of history. Soon after the Bell Labs/AT&T research trio published their findings, 34 companies raced to license semiconductor patents.[4] The semiconductor industry has metamorphosized significantly since 1947, though the integrality of the semiconductor in modern innovation remains constant. Watershed moments in each decade help explain how the industry has evolved as a function of evolving consumer expectations, business needs and an increasingly interconnected global ecosystem.

From the 1950s to early 1980s, the US dominated nearly every stage of the semiconductor value chain. Investment into semiconductor R&D surpassed that of all other nations, and government support for the young industry from both NASA and the Air Force proved critical in refining and commercializing ICs at scale. The 1970s marked the golden age of US semiconductor reign, though Japan trailed closely behind. For nearly two decades, Japanese semiconductor manufacturers struggled to generate comparable yields and profits. However, Japanese companies achieved a breakthrough as keiretsu banks aggressively mobilized capital for the semiconductor industry and the Ministry of International Trade and Industry offered low-interest loans, fast-tracked depreciation schedules, and funded R&D that enabled investment into equipment and domestic fab capacity. Japan's competitive advantage was further cemented through favorable trade practices, formation of a horizontally and vertically integrated semiconductor ecosystem, and a strengthened domestic supplier base. By the mid 1980s, Japanese producers achieved sufficient cost efficiencies and productivity improvements to push some US manufacturers out of the market. As a result, between 1982 and 1991, US market share for ICs plummeted from 57% to 39%, while Japan's market share climbed from 33% to 47%.[5]

As a first step to recapturing market share in both commodity and design-intensive chips, the US government renegotiated semiconductor trade agreement with Japan.[6] Soon after, Japan's banking sector collapsed, setting Japan into a prolonged recession known as the "Lost Decade" of 1990s economic growth.[7] Japan's semiconductor industry took a hit, while the US established new industry consortiums (e.g., Semiconductor Industry Association, Semiconductor Research Corporation, SEMATECH). And in Taiwan, the world's first pure-play foundry or semiconductor fabrication plant, Taiwan Semiconductor Manufacturing Company (TSMC) activated a fundamental industry shift from value chain integration to value chain specialization. In the 90s, US companies embraced the shift towards this new and flexible fabless/foundry business model. New fabless players such as Qualcomm and Xilinx began to outsource chip manufacturing to foundries such as TSMC, and instead focused on IP and design.

Over the past two decades, a series of natural disasters exposed the underlying fragility of the global semiconductor supply chain. In 2011, the Great East Japan earthquake and tsunami disrupted 75% of the world's supply of hydrogen peroxide (including Mitsubishi Gas Chemical, Adeka Fuji, and Nippon Peroxide) and created a shortage of 200,000 wafers per month for 2-3 months.[8] Japanese plant damages had a far-reaching impact, leading to the temporary closure of US-based GM truck plants in the absence of Japanese-made parts.[9] Floods in Thailand that same year further strained the industry, as Samsung faced a decline in DRAM prices and Lenovo constrained hard disk drive supply.[10]

Recent climate events have further fragmented a supply chain already strained by COVID-19. In the US, Samsung, NXP and Infineon suffered double to triple-digit revenue losses as a result of Winter Storm Uri and accompanying power outages in Austin, Texas fabs. A fire in one of Renesas' Japanese factories caused a 100-day return to normal production and roughly a $200M sales hit.[11] Taiwan's package substrate plant fires, power outages and ongoing drought have drawn attention to the region's outsized role in the foundry market.[12] Facing its worst drought in 50 years, the Taiwanese government has rerouted water supply from 20% of irrigated farmland and limited water access in 3 cities 2 days per week to help TSMC, the world's leading foundry, fulfill capacity.[13] To narrow the delta in water supply, TSMC is trucking in water from nearby regions and building desalination plants to ensure it has the 63M tons of water per year it needs to sustain production.[14]

Recent climate events have further fragmented a supply chain already strained by COVID-19

Stages in the semiconductor value chain

The symphony of global chip players forms the semiconductor value chain—the beating heart of the modern global economy. The collective value of these companies enables the design, build and delivery of semiconductors. Exhibit 5 below is just one example of a value chain flow, simplified for consumption.

Exhibit 5: Illustrative flows within global semiconductor value chain

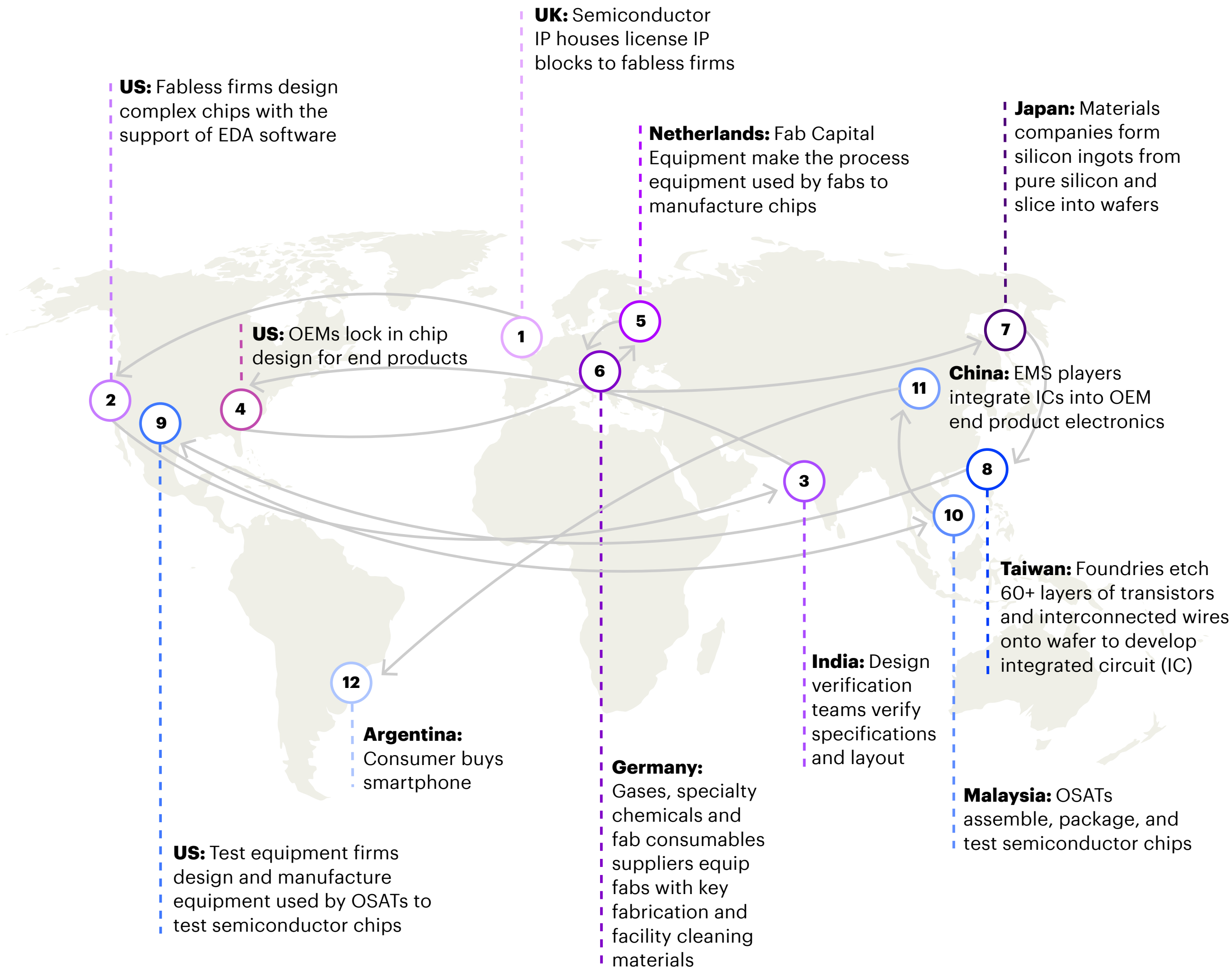
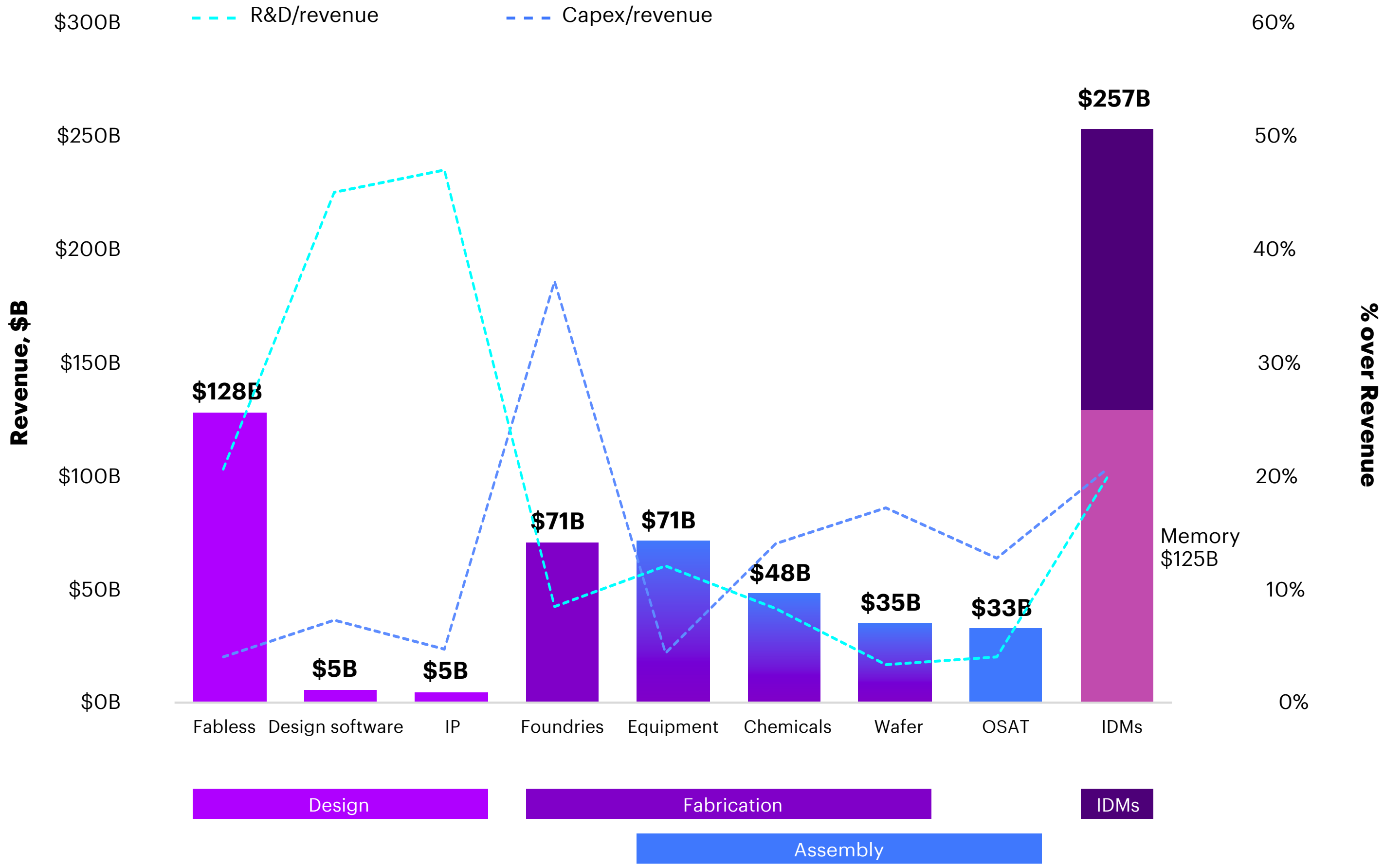


Exhibit 6: Revenue by semiconductor value chain segment (Accenture Analysis)



In this section, the report will explore the intricacies within each stage of the semiconductor value chain.

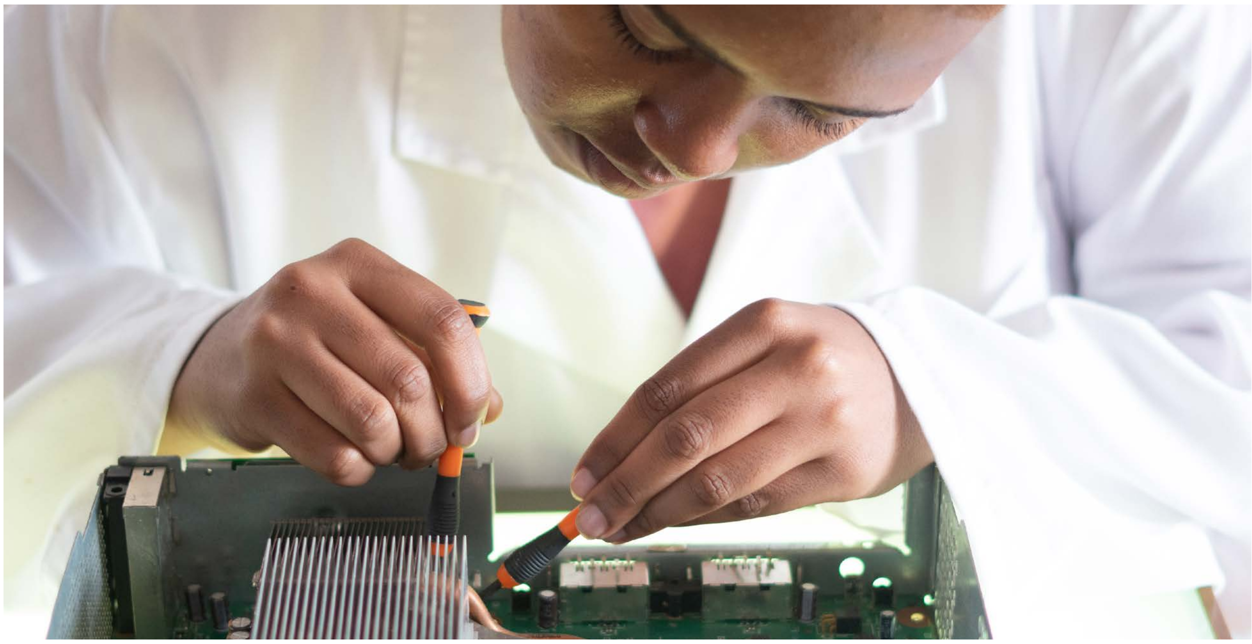
Exhibit 7: Design lifecycle

1. License IP cores from semiconductor IP houses
2. Integrate and harden IP cores from external vendors and in-house IP based on product requirements
3. Engage with EDA vendor for logical and physical design and floorplanning
4. Leverage verification teams to ensure design is functional and manufacturable at designated fab
5. Fab manufactures test wafer for final design validation

IP

Semiconductor IP defined

Semiconductor IP cores or IP blocks are reusable design components that are used to build ICs. IP players are critical upstream enablers of the design ecosystem as they support chip designers and expedite time-to-market offerings, selling the rights to design architectures and elements and reducing hardware-software integration risk. A simple analogy is to imagine each specific chip design as a modern home, and IP blocks as prefabricated sections (e.g., modular kitchen, appliances, etc.), designed and tested independently. In most cases, it is impossible or at least cost prohibitive to create new circuit designs from scratch, due to the amount of technical know-how and design verification and validation time needed. Instead, pre-designed blocks are used as a starting point. These blocks are owned by the IP house and are typically licensed to other companies who include these blocks as-is or further customize them for their specific applications.



Key players in IP

Arm, Synopsys, Cadence, Imagination Technologies, Ceva, SST, Verisilicon, Alphawave, Rambus

Recent advancements in IP

RISC-V: Originally intended as a research and teaching tool, RISC-V, an open source hardware instruction set architecture (ISA) has garnered notable interest globally. The ISA is free and open source, unlike its competitors ARM ISA and x86. ARM's propietary ISA requires licensing of canned IP blocks from ARM, and a top-tier license and a large in-house design team to customize and tweak ARM IP blocks further. x86 is a propietery ISA cross-licensed between Intel and AMD, and not available externally. RISC-V aims to disrupt the propietary IP players with an open-source model, reducing traditional barriers to entry for design, including design risk, cost of entry, and switching costs.

As expected, an industry focused on innovation and collaboration has reacted positively to this. Consumption of RISC-V CPU cores is expected to grow at a CAGR of 146% between 2018-2025, with the industrial and embedded sector driving the bulk of this growth.[15]

Electronic Design Automation (EDA)

Semiconductor EDA defined

Up until the 1980s, hardware design engineers laid out complex chip designs entirely by hand, sketching complex webs of transistor clusters and wiring all manually. Today, chip designs are much more complicated, and can contain tens of millions of logic gates (standard cells) and thousands of memory blocks (macroblocks), all meticulously placed and interconnected by several kilometers of wiring when fabricated.[16] For instance, when Google designed their next generation AI accelerator chip, they had to contend with more than 102,500 possible macroblock configurations, apart from millions of standard cells. The placement of these cells and blocks on the chip is critical to the functionality, speed, power consumed and cost of the chip. So EDA, and the algorithms contained therein are foundational to helping designers design chips - simulating functionality, integrating IP, optimizing floorplan and verifying designs. Foundries have also come to depend on EDA tools, particularly when presenting coded versions of their manufacturing processes (design rules checks) to design houses to ensure manufacturable chip layouts and reduction of prototyping cycles (design-technology co-optimization).

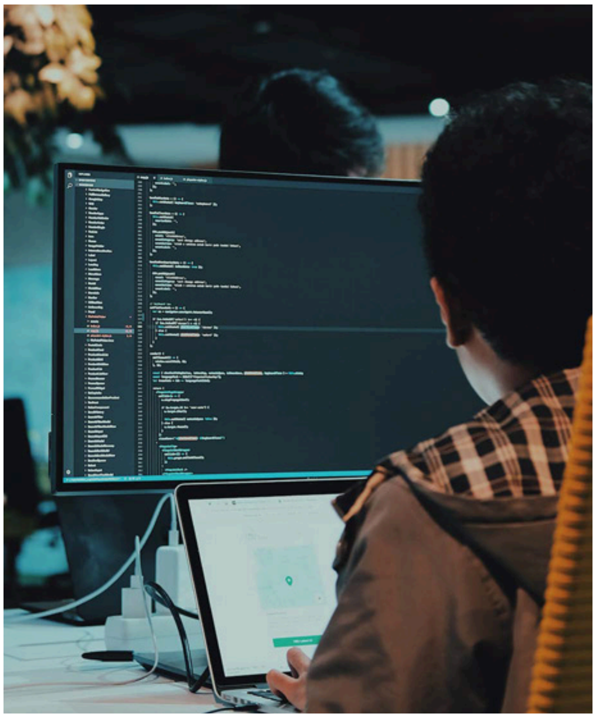
Given the increasingly complex chip design requirements for cloud, high performance computing, 5G, AI/ML, IoT, and edge computing capabilities, EDA companies have been prolific acquirers of smaller IP houses to provide integrated, synergistic IP solutions along with their EDA software, becoming significant semiconductor IP houses in their own right.[17]

Key players in EDA

Cadence, Synopsys, Mentor Graphics (Siemens)

The world's leading EDA vendors are concentrated in the US, controlling 70% of the global market for EDA tools.[18] These players dominate the market, considering how tightly integrated EDA tools are with existing chip process flows and how difficult it is for semiconductor manufacturers to switch EDA vendors.

Recent advancements in EDA

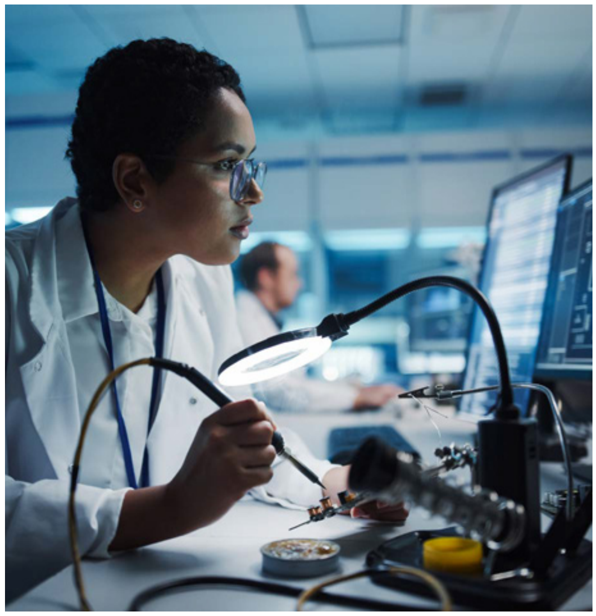


Cloud and AI-powered EDA: In the last two years, there as been a marked movement of the EDA industry from an on-prem computing model (at the fabless or foundry company's premises) to a cloud service deployment model. Historically, the on-prem was favored due to concerns over protection and control of IP and highly sensitive data such as foundry design rules and process design kits. But as Moore's law progresses (albeit more slowly), each node almost doubles the number of transistors that needs to be designed and verified by the EDA software. Moreover, as manufacturing gets more technically challenging with each new node, the number of design rule checks have expanded, increasing EDA compute demand by 20-30% for each new node. This in turn has ballooned design and verification costs. The major public cloud vendors, sensing an opportunity, have started to address the IC industry's security concerns adequately. Presently, all three major EDA players have services available on the most popular public clouds. Cloud platforms are designed to scale to an extremely large number of resources. Cloud-native EDA platforms also make it easier to integrate the latest innovations in AI to markedly improve performance. For instance, Google engineers proved these benefits in a recent study where they trained an AI-based EDA "agent" that performed floorplanning design in under 6 hours, a task that would take human designers months of effort.[16, 19] All major EDA vendors and fabless companies are investing in this game changing capability.[20, 21]

Homegrown EDA Hub in China: China represents a growing revenue share for the three large EDA companies. In 2017, Synposys set up a $100M strategic investment fund to expand engagement with chip designers in China. In response to trade tensions and access to Western EDA products, China renewed its own EDA sector by investing in home grown startups and recruiting talent from the large global EDA vendors.[18]

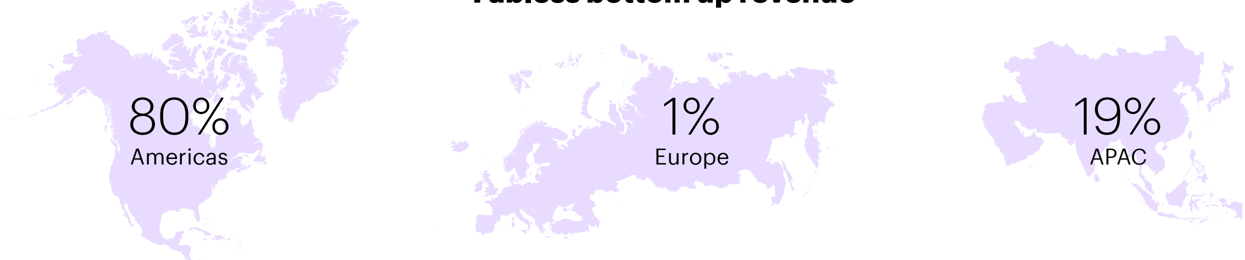
Design

Semiconductor design defined

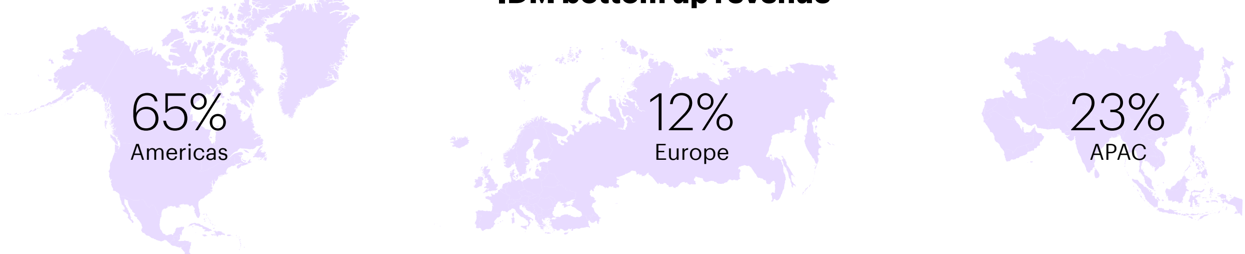


Foundational to semiconductor design is determining chip size, placement of memory and logic, and interconnections among a chip's transistors and gates. Simple designs contain hundreds to thousands of transistors per chip, whereas complex designs can house 2 billion transistors per chip.[22] **Design dictates the holy grail of a chip's power efficiency and processing speed, the combination that governs which chips power particular end applications**. Though EDA tools are instrumental in simulating, testing, and refining chip design, the design process remains labor, time, and cost intensive. The costs associated with designing for advanced 3nm nodes, for example, range from $500M to over $1.5B. Chip design costs for mature nodes have also surged to nearly $50M for 28nm, $298M for 7nm, and ~$542M for 5nm chips.[23] Design is the most R&D-intensive stage of the value chain—and the fundamental enabler of silicon technology. Design projects typically last for 4-5 years.

Fabless bottom up revenue



IDM bottom up revenue



Additionally, design companies partner closely with manufacturing—whether internal or external. As the key player in understanding what needs to be made, their input into manufacturing process and methodology is critical. Without input and collaboration from design companies, semiconductor manufacturers would not be able to execute core foundry capabilities.

Key players in design

Fabless: Nvidia, Broadcom, Qualcomm, AMD, Xilinx, Huawei HiSilicon, MediaTek

IDM: Samsung, Sony, SK Hynix, Kioxia, Renesas, NXP, Intel, Analog Devices, Texas Instruments, Micron, Skyworks, Infineon, STMicroelectronics

Design companies, including fabless and IDM, continue to play a pivotal role in sustaining innovation in this stage of the value chain

Recent advancements in design

Despite significant barriers to entry into chip design, hyperscalers are quickly realizing the value potential in design and beginning to cement their foothold in this stage of the value chain. Design powerhouses are experiencing competition from software behemoths, who are designing in-house chips to reduce costs, unlock performance gains and hyper-customize chip functionality for specific use cases.

Exhibit 8: Hyperscalers inching into design

Embedding in-house processors within iPhones, iPads, and Macs, in a move away from Intel. Custom chips unlock new 'art of the possible' functionalities (e.g., facial recognition, AR)[24]

Trading NVIDIA chips for fit-for-purpose in-house chips. Partnering with TSMC & Samsung on next-generation 7nm & 5nm chips for use in self-driving cars[25]

Leveraging Annapurna Labs acquisition to supercharge in-house design of Inferentia chips optimized for Alexa & Echo voice assistant and facial recognition[26]

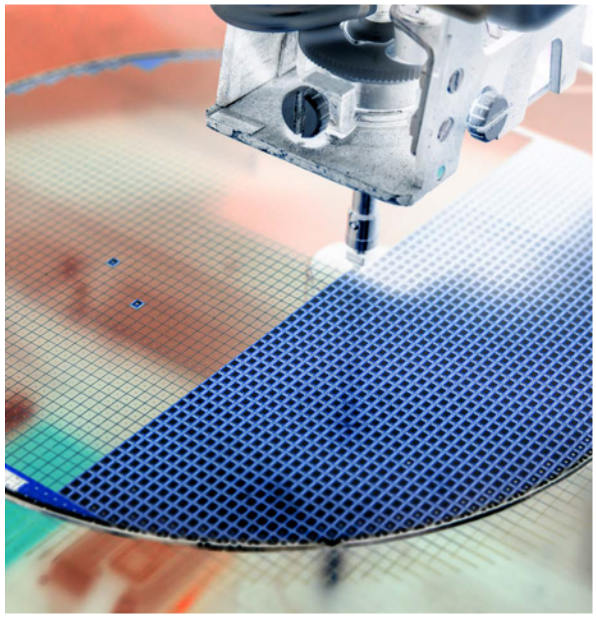
Aiming to shift away from AMD & Intel to in-flight, in-house chips to run Surface PCs and cloud computing services[27]

Using in-house chips for Chromebooks to replace CPUs provided by AMD, Intel, and MediaTek[28]

Using in-house Hanguang 800 chips for AI applications, including intelligent customer service[29]

Fab, bump, wafer sort (front-end manufacturing)

Semiconductor front-end manufacturing defined



Front-end semiconductor manufacturing is a rather complex and unforgiving process that requires a 99.99% yield at minimum for each precise step to produce a viable semiconductor end-product.[22] Manufacturing begins with a cylindrical crystalline ingot, which is then sliced, polished, and patterned into thin wafers of different diameters. While silicon is usually the material of choice for most semiconductor devices, alternate materials including gallium arsenide, gallium nitride and silicon carbide may be used, depending on the type of device being fabricated. As end applications for semiconductors diversify, so do the opportunities to utilize these silicon alternatives.

Once the fab receives a batch of wafers, fab engineers use complex lithography, etching, implanting, planarization, passivation, and deposition techniques to build out upwards of 60+ layers of transistors with an interconnect network of wires to connect the transistors. Wafer fabrication can be a 350-step, 45-60-day process in a mature node or 700+ step, 60+ day process in an advanced node.[22] Either way, **semiconductor fabrication is a methodical, orchestral masterpiece—a precise harmony among several thousand tools, pieces of equipment, and materials**.

Key players in front-end manufacturing

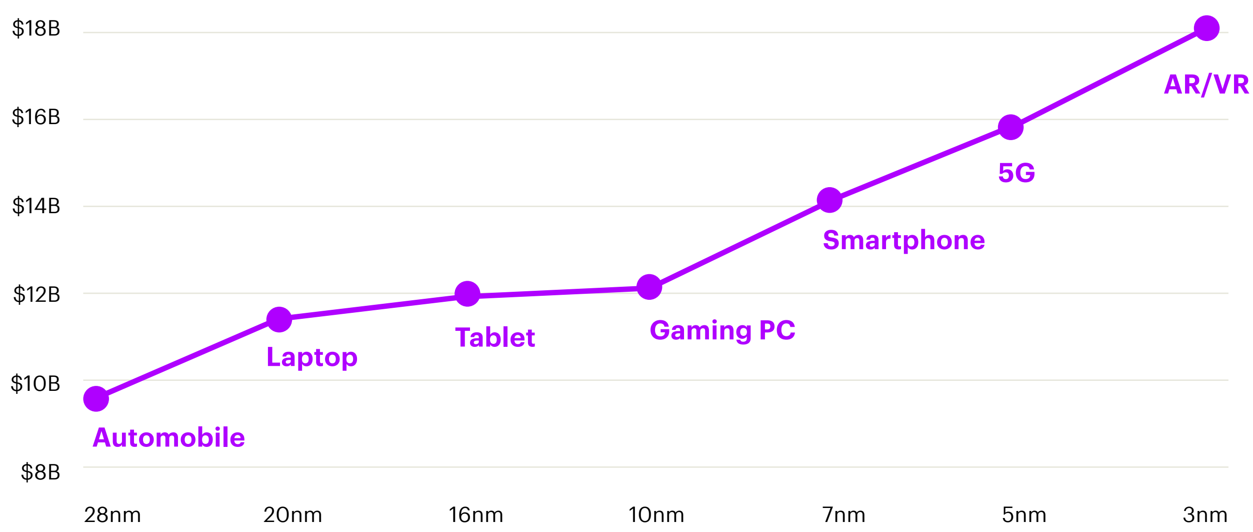
TSMC, Samsung, UMC, SMIC, GlobalFoundries are major foundries providing front-end manufacturing services. IDMs such as Intel, Micron, NXP, Texas Instruments, and Infineon perform front-end manufacturing in-house. These companies operate semiconductor wafer fabrication facilities, with typical volumes above 50,000-100,000 wafers per month. Large foundries such as TSMC have multiple fabs with total wafer capacity of much larger than that. Most front-end manufacturing occurs in East Asia, with some clusters in the US and Europe.

> Semiconductor fabrication is a methodical, orchestral masterpiece

Recent advancements in front-end manufacturing

As Moore's Law progresses and transistor size keeps getting smaller, front-end manufacturing complexity and its associated cost is skyrocketing. The graph below shows the cost from the front-end manufacturing equipment alone for various technology nodes. Excluding the rest of the infrastructures needed to build a greenfield fab (e.g., utilities, buildings, process development), 3nm is projected to cost $18B.

Exhibit 9: Greenfield equipment cost (source: Applied Materials)



Front-end manufacturing is the most capital-intensive part of the semiconductor value chain and has been recognized by ecosystem members and governments around the world. The governments of Taiwan and South Korea view front-end manufacturing as an important industry sector and have been providing support to the industry. Recently in the US, Intel announced their plan to start offering foundry services, and shortly after the company also made news that it was one of the awardees of Department of Defense's RAMP-C program (Rapid Assured Microelectronics Prototypes—Commercial). Through this program, the Pentagon aims to build up domestic design and manufacturing of cutting-edge semiconductor chips. Other awardees of this program have included IBM, Synopsys, and Cadence.[30]

Being the most capital-intensive part of the value chain means that as a fab moves on to the next generation technology node, it will have to invest in larger amounts of capital to build capacity. As an illustration, Samsung announced that it would be investing $205B into their chip production and biotech line of business over the next 3 years.[31] It is anticipated that a large portion of this amount will go into Samsung Electronics, which specializes in memory chips and foundry business. Samsung also projected to increase its R&D and CapEx by 33% over the average of the last 3 years. On another note, the only other foundry capable of leading node front-end manufacturing, TSMC, is investing $100B into additional chip capacity over the next 3 years. **From these announcements, it is clear that an intense level of capital is needed to be at the forefront of leading-edge front-end manufacturing**.

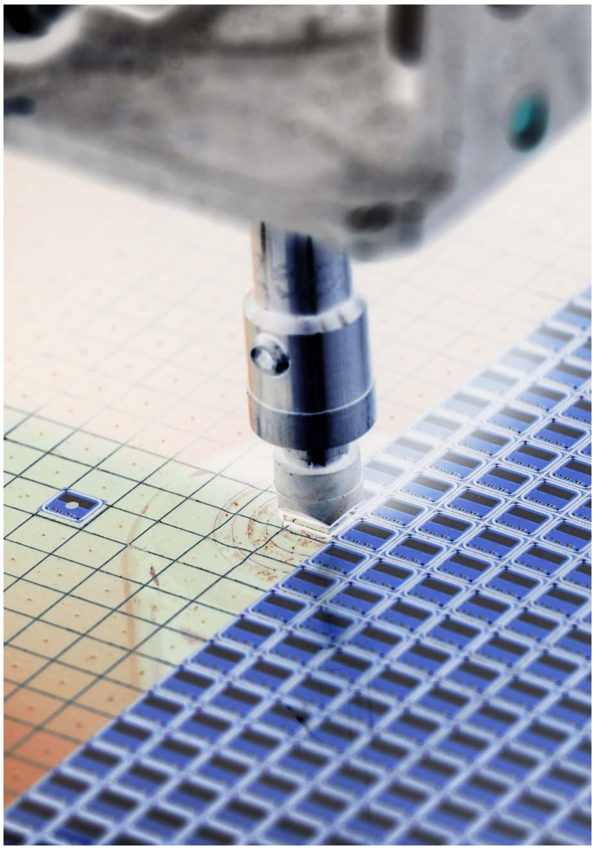
Exhibit 10: Advantages and disadvantages of IDM vs. Foundry business model

	Benefits	Risks
Integrate device manufacturer (IDM)	• Vertically integrate model enables design and manufacturing process to always be in lockstep • High margins attained due to lack of dependency on 3rd parties • Able to squeeze value on established market trends • Better at staying on top of demand through greater visibility into end-to-end supply chain (e.g., Toyota during COVID-19 pandemic)	• Forced to fill the factory to avoid idle fabs, even in times of lower customer demand • Only one customer means design plans are inherently riskier in the absence of external customer to validate • Scattered mangement focused across design and manufacturing makes it difficult to catch up
Foundry	• Clear understanding of long-term demand shifts and customer preferences from broad swathe of end verticals • Nimble; often first to market in new product categories • Risk pooling: CapEx spread across diverse customer portfolio and technology co-developed with broad set of customers • C-suite is laser-focused on foundry operations • Customer-centricity	• Non-strategic fabless firms have minimal collaboration with leading foundaries • Margins may be capped through second sourcing and competition • Agility depends on degree of customer relationship

Package, assembly, and final test (back-end manufacturing)/OSAT

Semiconductor back-end manufacturing defined

Wafers are shipped to outsourced factories, which operate on high labor costs, low margins, and immaculate operational efficiency. Companies in this stage of the value chain play a critical role in packaging chips into a form that improves reliability and enables connectivity with other circuit components, testing for target functionality, performance, and reliability specifications. Each individual chip is probed before slicing the wafer into die and packaging between substrates and heat spreaders. Packaged chips are then sent to assemblers, who assemble chips into circuit boards with passive components and protective encasing. As in all other areas of the semiconductor value chain, OSATs are experiencing rising costs, leading many semiconductor firms to bring in-house packaging, assembly, and test capabilities to minimize costs and supply chain bottlenecks.[32]



Key players in back-end manufacturing

Amkor, Teradyne, JCET, ASE Group, Powertech

Most packaging, test, and assembly houses are in lower-cost locations, including Malaysia, Vietnam, China, and Taiwan. CapEx for back-end facilities is comparably lower than for front-end fabs.

OSAT bottom up revenue

Recent advancements in back-end manufacturing

Advanced packaging: The industry is experiencing a renaissance in advanced packaging to enable the shift towards increasingly complex chip designs. Across 2.5D/3D, chiplets, fan-out, and system-in-package (SiP) technologies, design houses are faced with boundless configurations to assemble and integrate complex dies into advanced packaging—all of which serves to differentiate new chip designs. The emergence of this technology as an option in semiconductor manufacturing further highlights the importance of collaboration across all stages of the semiconductor value chain, as silicon design has an increasing impact on advanced packaging capabilities.

2.5D: Dies stacked side-by-side on top of an interposer; unlocks memory bandwidth gains at lower power point

3D: Logic stacked on memory, or logic stacked on logic; providing more memory packed into a smaller area

Chiplets: Connected set of mix-and-match dies; improves yield and lowers cost

Fan-out expands: DRAM stocked on top of logic, without the interposer; geared for 5G-enabled mobile smartphones and IoT devices

System-in-package (SiP): Several components (e.g., antennas, dies, MEMs, passives) integrated into a single package that functions as an electronic system; suitable for various products, ranging from automotive to smartphones, home power management, and watches

Though most chips are assembled into mature commodity packages, advanced packaging is playing an increasingly important role across the industry as semiconductor players chase after performance gains and smaller form factors. Samsung is working on two advanced packaging initiatives in tandem: 3D memory-and-logic stacked technology and packaging that combines memory with AI processing. TSMC, ASE, and Amkor are co-developing high-end fan-out packages that integrate logic and an increased number of memory cubes. i3 Electronics is producing SiP stacking technology and many other semiconductor players are producing chiplets.[33]

Geographic concentration poses vulnerabilities: Disruptions in back-end semiconductor manufacturing are surfacing due to the impact of COVID-19 in Southeast Asia. Malaysia, a back-end manufacturing hub that accounts for 13% of global semiconductor packaging and assembly, continues to experience aftershocks from nationwide shutdowns in the summer of 2021 and a record number of new COVID-19 infections due to the delta variant.[34] Malaysian OSATs were tagged as essential businesses and allowed to operate at 60% capacity, but shutdown of the sector triggered a domino effect in downstream repercussions.[34] Given how labor-intensive this stage of the value chain is, disruptions in factory output acutely impacted semiconductor companies and key automotive players across the globe.

China's rising presence in OSAT: As shown through JCET's acquisition of STATS-ChipPAC and Tongfu's acquisition of AMD packaging factories, China is successfully using M&A as a catalyst for growth in back-end semiconductor manufacturing. Acquisitions in this space have enabled smaller Chinese OSATs to leapfrog the competition in capability breadth and depth. JCET's latest acquisition, for example, equips the company with advanced fan-out, flip chip, and advanced test capabilities and a customer base including Apple, Qualcomm, and HiSilicon. Similarly, Tongfu's acquisition of China's back-end factories allows the company to inch deeper into flip chip assembly and test.[37] **Chinese OSATs are projected to continue growing, which only further supports China's agenda to achieve self-sufficiency in the semiconductor supply chain**.

Semiconductor impact[35]

Infineon: High double-digit million-euro sales impact in Q3, with a lowered Q4 outlook

NXP + STMicroelectronics: Closure of Malaysian facilities

Globetronics Technology: Closure of 2 factories, four-week recovery period to get deliveries back on track

Automotive impact[35, 36]

Ford Motor: Temporary suspension of production of F-150 pickup trucks at Kansas City, Missouri plant, closure of Fiesta factory in Cologne, Germany

Toyota: Cut production by 40% in September

General Motors: Producing 100K fewer vehicles in North America in 2H CY 2021

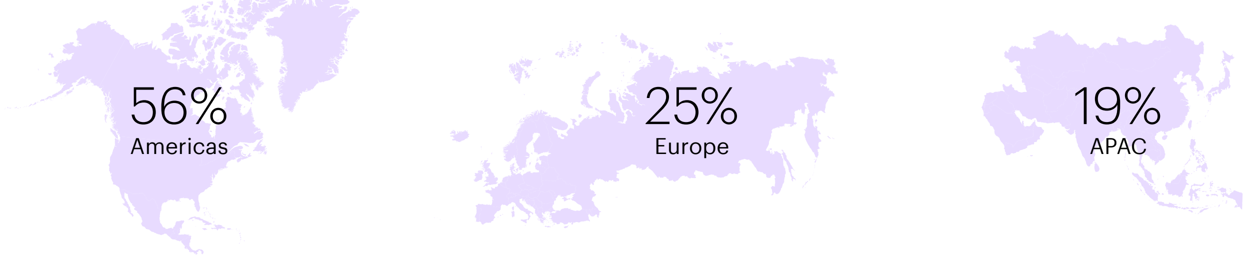
Nissan: 2-week suspension of Leaf EV/Rogue SUV Smyrna, Tennessee plant (one of the longest automotive plant closures seen due to Malaysian OSAT shutdown/disruption)

Equipment

Semiconductor equipment defined

Equipment drives the bulk of fab capital expenditure, as each fab depends on several hundred distinct pieces of equipment from multiple vendors. Many types of semiconductor equipment exist but can be categorized into three broad categories: wafer fabrication and processing equipment, test equipment, and assembly/packaging equipment. Each piece of equipment costs on average $2M – $6M, price tag representative of decades of intense R&D and ecosystem collaboration. Despite the price tag, a typical semiconductor manufacturing equipment depreciates after 5 – 8 years in operation. To top this off, manufacturing equipment incurs significant ongoing costs due to maintenance and hardware/software upgrades.

Equipment bottom up revenue



Key players in equipment

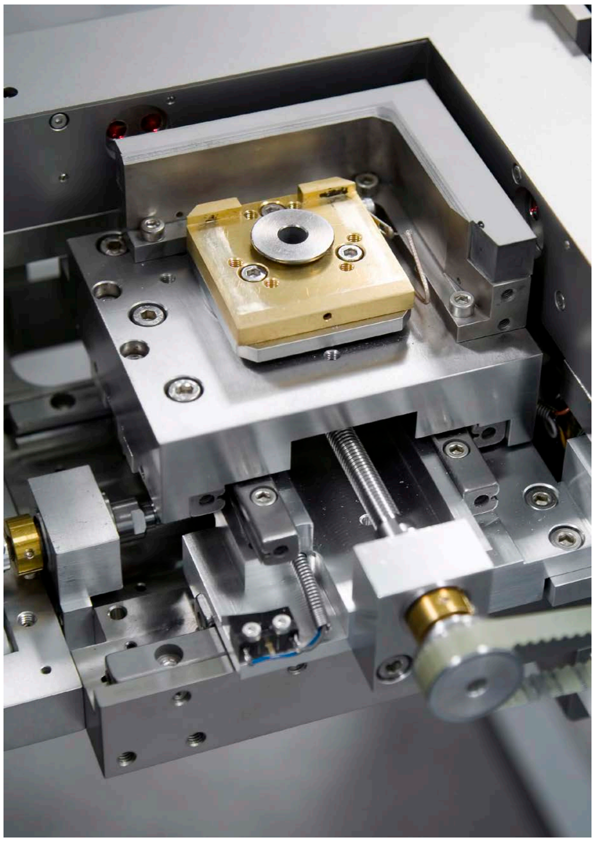
Though the world's leading semiconductor equipment vendors offer a breadth of equipment types, each player specializes on specific steps in the fabrication process.

Equipment vendor	AMAT	LAM Research	KLA	ASML	Tokyo Electron
FY20 revenue	**$17.2B**	**$10.0B**	**$5.8B**	**$16.5B**	**$10.3B**
Focus area(s)	Plasma etching equipment; deposition, etch, ion implantation, rapid thermal processing, CMP	Plasma etching equipment; systems integral in film deposition, plasma etch, photoresist strip, wafer cleaning	Metrology equipment for quality control; process control systems	Photolithography equipment, including EUV (extreme ultraviolet lithography) equipment to produce chips smaller than 7nm (leading node)	Thermal processing, photoresist coating/ developing, wet surface preparation, CVD, wafer probing

Recent advancements in equipment

ASML's newest $150M Extreme Ultraviolet Lithography (EUV) machine is roughly the size of a bus and contains 100,000 parts and 2 kilometers of cabling, all of which require 40 freight containers, 3 Boeing 747 airplanes, and 20 trucks to transport from Connecticut to the Netherlands.[38] Then, it takes a group of field engineers 4 – 6 months to install, test, and validate the machine. **Lauded as the golden ticket to sustaining Moore's Law innovation for at least another decade, ASML's latest EUV machine is expected to enable the world's fastest, most-efficient chips**. However, this breakthrough did not happen overnight. Several key semiconductor manufacturers have been co-investing in ASML's EUV technology since the 1990s. After decades of R&D, ASML finally commercialized EUV machinery in 2017. TSMC has been the leading foundry to capitalize on EUV technology, supplying customers such as Apple, NVIDIA, and Intel with ever-miniaturized chips that power advanced robotics, biotech devices, and smartphones. Though historically behind TSMC in its use of EUV machinery, Intel is expected to be the first foundry to produce chips using ASML's new machine in 2023.

While ASML drives continued technological advancement in the semiconductor industry, it is powered by an ecosystem of partners, including Tokyo Electron & LAM for photoresist tracks, ZEISS for optical lenses, and a host of Asia-based photoresist manufacturers for materials. Using ASML as a case study, no dominant player in any stage of the value chain can successfully operate without a highly global network of suppliers—and any disruption to collaboration has the potential to interrupt decades-long investments from semiconductor players all over the world.



Export control restrictions have prevented access to ASML's technology in China. In an example of the importance of cross-border collaboration, restricted access to critical equipment for semiconductor manufacturing will challenge any company's ability to make the most sophisticated chips.[39]

Materials

Semiconductor materials defined

Chemicals, gases, minerals, and high-purity materials are integral to semiconductor fabrication (e.g., patterning, deposition, etching, polishing), equipment operations, facility cleaning, and packaging. **Wafer fabrication requires nearly 500 specialized process chemicals, with the number and amount of chemicals continuing to rise as semiconductors become more complex**.[40] As semiconductors become smaller, there is also a need for new materials (e.g., replacements for copper, metal) to connect transistors. As such, materials companies and foundries are engaging in joint R&D programs to ensure advances in semiconductor design and manufacturing are understood and enabled, not bottlenecked, by materials.

Key players in materials

Japan (Shin-Etsu, Sumitomo Chemicals, Mitsui Chemicals), Europe (BASF, Linde, KGaA, Darmstadt, Germany), Taiwan Specialty Chemicals Corporation, US (Dow/DuPont).

Semiconductor materials companies often supply several other industries (e.g., pharmaceuticals, industrial, agriculture), leading this stage of the value chain to be less vulnerable to semiconductor industry shocks than other stages of the value chain. Semiconductor materials suppliers are positioned across the world, though remain largely concentrated in Japan, South Korea, and Europe.

Disruptions in semiconductor materials can have far-reaching ramifications across the value chain. TSMC experienced this firsthand when the foundry inherited an abnormally treated batch of photoresist chemicals, forcing the company to abandon a batch of silicon wafers that resulted in a $550M sales hit.[41]

Recent advancements in materials

Rise in non-silicon-based semiconductors: Silicon is the industry's long-standing winner due to its manufacturability. It is the cornerstone of memory and logic devices, which account for most semiconductor products. **But as consumer demand for clean energy, electric vehicles, 5G, and IoT sensors rises, the industry is in an R&D race to uncover new materials for non-silicon-based semiconductors**. The world's leading fabless players, IDMs, and foundries are partnering together and with academia to discover what new materials can be produced at scale, integrated into existing electronics, mixed with silicon, or substitute silicon altogether. Though unlikely to replace silicon, graphene prevails as a promising addition when combined with silicon, offering qualities that uniquely enable high-resolution infrared cameras and ultra-thin ultra-sensitive cameras[42]. Molybdenum disulfide, already in use within flexible electronics and microprocessors, also shows potential. Some new materials are used in commercial end applications today, but the next decade of R&D will prove pivotal in uncovering precisely what 2-D materials—black phosphorous, transition metal dichalcogenides, boron nitride nanosheets, tungsten disulfide, and others—will offer the right mix of traits and manufacturability at scale to sustain Moore's Law and meet demand for once-niche end applications.

Shift to advanced node creates need for new materials: With growth in advanced node technology, innovations in material science are required to increase electron mobility and transistor speed. More materials are needed: wafers, etch gases, precursors, photoresists, and CMP consumables. New materials are also needed to perform extreme ultraviolet lithography (EUV), high-resolution etch and deposition, and various other steps at nanometer scale dimensions. Hafnium, cobalt, ruthenium, molybdenum, gallium nitride, and graphene are among the new materials that have been incorporated into leading-edge manufacturing. New mask absorber layers, advanced resists, polish slurries, photomasks, and deposition targets are also in use. For example, Professor Yongjie Hu, mechanical and aerospace engineering researcher at UCLA's Samueli School of Engineering, recently discovered a new ultra-high thermal-management material: boron arsenide.[43] More effective than silicon carbide and diamond in dissipating heat, boron arsenide lowers processor heat build-up, thereby boosting energy efficiency in high-power devices. For all new materials, fabrication process complexity significantly increases, in part because advanced filtration and purification mechanisms are necessary to ensure material integrity during manufacturing.

Advanced packaging revolution: Materials will play a crucial role in fueling the advanced packaging revolution, particularly as advanced packaging grows at double the pace of overall packaging. With the shift towards smaller, thinner packaging, new substrate designs, laminate materials, mold compounds, fillers, die attach materials, dielectrics, and depositions are needed. A snapshot into new materials needed to propel advanced packaging innovation are outlined below:

Exhibit 11: Materials to power advanced packaging innovation

- Laminate substrates for System-in-Package
- Electroplating materials for copper redistribution layer
- Die attach materials with no-to-low resin bleed & outgassing
- New substrate designs to enable narrow bump pitch
- Dielectrics with lower dielectric loss for high-frequency use cases like 5G
- Mold compounds for flip chip

Original Equipment Manufacturers (OEMs)

Semiconductor OEMs defined

OEMs are companies that design and deliver the end products to consumers. The end products powered by semiconductor chips used to be a relatively narrow class of hardware such as personal computers, mobile phones and communication equipment. However, in the past two decades, existing and new OEMs have emerged with various offerings, ranging from smart watches, home electronics, drones to tractors, industrial robots, and motion sensors. Semiconductor OEMs typically design the end products using their in-house engineering capabilities and source their chips from either IDMs or fabless companies. Recently, however, there has been a move by major OEMs to develop their own design capability in-house and outsource the manufacturing part to foundries. OEMs often engage with EMS partners for their packaging and assembly needs.

OEMs in the semiconductor value chain have the closest relationship with the end consumers and thus, have the best vantage point of market dynamics and preference. The end products are designed to cater to consumers' needs and/or tastes, with the semiconductor chips being the brains powering those products. Hence, it is expected that more OEMs will be interested in getting intimate knowledge of the very components that enable their products' applications. Additionally, with high performance semiconductors present in more devices nowadays, OEMs have also shifted from being mostly personal computer and mobile phone makers to also being car and LIDAR makers.

Key players in OEM

Apple, Samsung, Huawei, Lenovo, Dell, HP

Recent advancements in OEM

Two big moves by semiconductor OEMs in recent years were the involvement in the design of the chips that power their devices and the wide variety of frontier applications due to the proliferation of ASICs.

Vertical integration

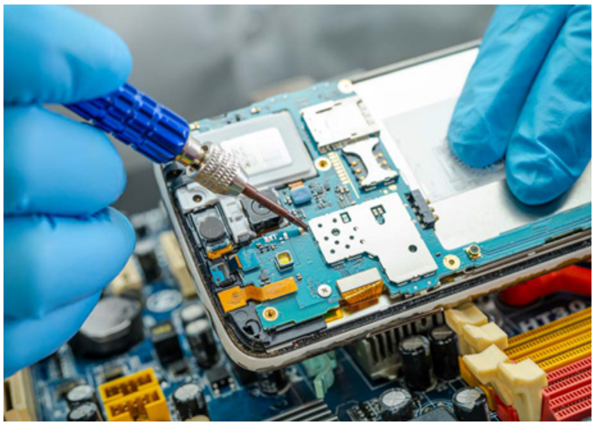
Major OEMs such as Apple and Huawei have in-house chip design capabilities that allow them to tailor their chips to be optimized for the end products' use cases. Prior to 2010, Apple used x86 chips designed and manufactured by Intel to power their Macs. However, Apple reportedly started their own in-house chip design effort in 2008, using the Arm architecture as opposed to Intel's x86, through their $278 million purchase of P.A. Semi. Since 2010, Apple has been using their in-house designed chips to power their iPhones, iPads, Apple Watches, and more recently, laptops and desktops. TSMC has been Apple's major foundry partner, though others such as Samsung and GlobalFoundries have also been reported to manufacture Apple's chips.

The rise of custom ASICs

By owning in-house chip design capabilities, OEMs have the know-how to venture into new areas and applications from a semiconductor requirement perspective. For example, OEMs producing high-performance desktops can optimize their design to focus on the high-compute aspect. On the other hand, OEMs that compete in the smart watch space can tailor their chip design for superior power consumption. By mastering the design of their ASICs, OEMs can optimize the PPAC (e.g., Power, Performance, Area, Cost) for their specific products' applications.

Electronics Manufacturing Services (EMS)

Semiconductor EMS defined



During the recession of the early 1990s, original OEMs could not afford the capital investment of new equipment and turned to Electronics Manufacturing Services (EMS) providers to take on greater manufacturing risk and costs.[44] Since then, OEMs have increased their reliance on EMS players, who have broadened their scope well beyond outsourced manufacturing services. EMS providers have become the "foundries" of the OEM enterprise, offering a breadth of services including demand forecasting, supplier management, inventory management, materials procurement, outbound logistics, delivery, warranty repair, and customer service support. **Through increased reliance on EMS providers, OEMs achieve volume scalability, mass customization, reduced time to market, and supply chain and logistics efficiencie**s. Economies of scale are easily realized, as a relatively similar set of parts (e.g., resistors, capacitators, memory) are constructed in similar fashions across an assortment of product configurations, meaning EMS providers can maximize capacity utilization across various work orders for a diverse set of OEMs. Most EMS players are concentrated in Asia, given the region's low overhead, low labor costs, and operational success in producing high-volume, low-margin goods. However, large EMS players have increasingly built production sites across the world to minimize transportation spend and be closer to OEM's end-consumer markets.

Key players in EMS

Foxconn, Jabil, Flextronics; EMS player Foxconn has achieved unparalleled scale, employing nearly 1.3M people and touching 40% of electronics worldwide.

Recent advancements in EMS

Leading EMS firms such as Foxconn are edging into upstream stages of the value chain. As the largest assembler of iPhones, Taiwan-based Foxconn is expanding its semiconductor ambitions and has been on a purchase spree, buying semiconductor manufacturing facilities across Taiwan and forging strategic partnerships throughout the ecosystem. Headwinds include the EMS firm's partnership with ARM, the $3.5B acquisition of Sharp, and the construction of a Qingdao-based semiconductor packaging and testing plant. Foxconn's latest alliances with Fisker and Stellantis and a purchase of a six-inch wafer facility will further enable the EMS player to make a formidable entrance into EV assembly.[45] In addition, Foxconn's latest "XSemi" joint venture with Taiwan-based Yongeo Corporation further deepens its footprint into the semiconductor ether, activating Foxconn's 3+3 strategy to enter three end verticals—smart healthcare, EVs, and robotics—and focus on three technologies—semiconductors, AI, and next-generation telecommunications.[54]

Macroeconomic trends

TREND 1

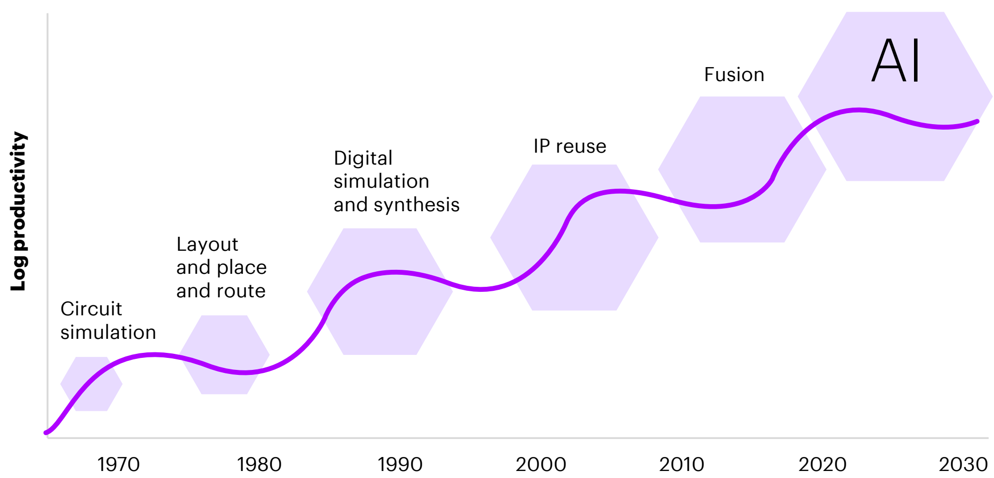
Slowdown of Moore's Law

One of the most widely discussed industry phenomenon has been the slowdown of Moore's Law. Semiconductor companies have achieved relentless innovation in the 50+ years of Moore's Law, which posits that the number of transistors doubles every 18-24 months. Moore's Law supercharged industry innovation, motivating semiconductor companies to exponentially increase computing power while decreasing the cost of the chips. Chips are now smaller, denser, and more powerful than ever before. Relative to other industries, Moore's Law has propelled the semiconductor industry to achieve an unparalleled pace of innovation. Estimates show that an average of 7.6 trillion transistors are created per second—which equates to more than 25.4x the number of stars in the Milky Way or 76.1x the number of Galaxies in the universe.[55] **To further contextualize, if Moore's Law were applied to the automotive industry, an SUV from the early 2000s would have the horsepower comparable to that of a large passenger jet engine.**[55]

Exhibit 12: Moore's Law: The propellant for semiconductor industry innovation (Source: Our world in data—Karl Rupp, 40 years of microprocessor trend data)

Gordon Moore's vision for exponential semiconductor growth has become the self-fulfilling prophecy driving technological improvement. However, keeping pace with Moore's Law is becoming economically unviable for many players as fab costs increase, transistors shrink to atomic proportions, and semiconductor process technology becomes more complex. The semiconductor industry is now experiencing a slow-down of Moore's Law, with some industry executives suggesting that Moore's Law simply is not possible anymore.[56] Recent advancements have generated less impact in power reduction, density, and performance, which creates a major challenge as the industry seeks to move AI processing from the cloud to the edge to meet booming demand for Smart-X products.[57] Beyond the Smart-X ecosystem, the plateau in Moore's Law has ramifications on virtually every industry that depends on computing technology. Semiconductor companies are chasing after lower power consumption, reduced heat generation, and robust chip architecture gains that transcend performance[58].

However, players across the value chain are venturing to break through the plateau. In advanced packaging, Intel is investing in 3D chip stacking, with two layers of logic dies and one layer of DRAM, to advance ultralight device performance[59]. EDA toolmaker Synopsys is venturing to define a new era of Moore's Law called "SysMoore" marked by hyper-convergent AI-led chip design.[60]



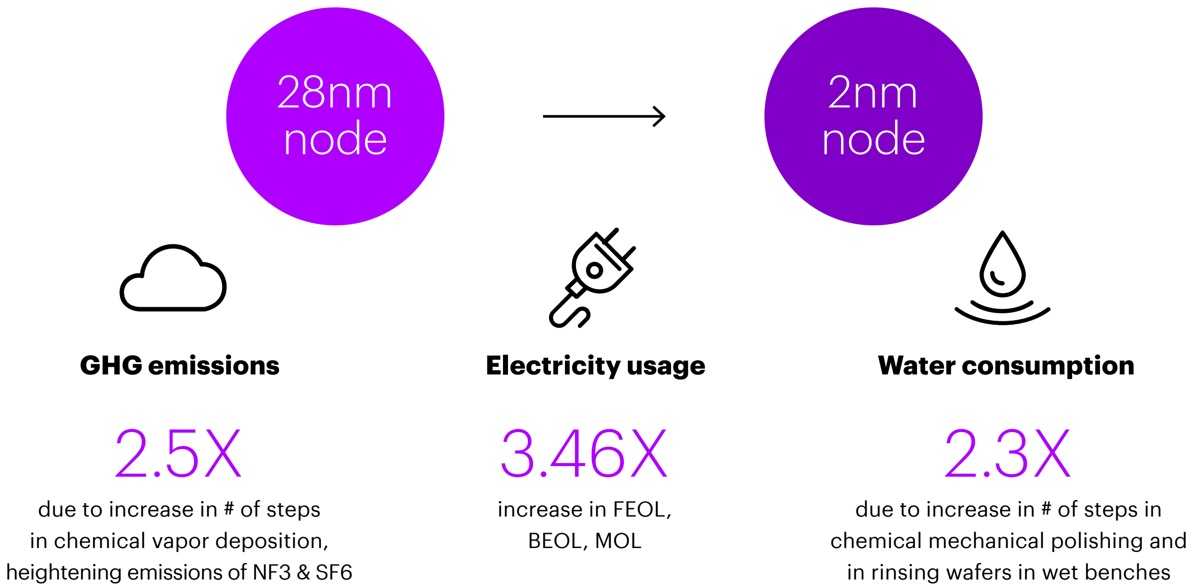
Beyond advanced packaging technologies and AI-powered chip design, software-hardware co-design presents a high-impact opportunity to unleash a new level of innovation. For the past 50+ years, hardware advances alone catapulted the industry along Moore's Law innovation trajectory. But with incrementally smaller improvements in hardware, software-hardware co-design will be increasingly important, both within semiconductor companies and across companies in the semiconductor ecosystem. Hardware and software development efforts remain largely disconnected, with each built through different coding languages, using different methodologies, and by engineering teams that have limited interaction. **Co-design requires a bottoms-up revolution in how engineering teams currently work, with engineers adopting one consistent coding language and new design values, tools, and stage-gate processes**. Interlock between hardware and software will be pivotal, so that changes in hardware translate to near real-time changes in software, and vice versa, thereby eliminating the multi-month or -year lag that currently exists.

TREND 2

New emphasis on sustainability

Global commitment to sustainability initiatives under the Paris Climate Agreement has made it clear that every industry will play a critical role in transitioning to net-zero emissions.[61] A growing number of semiconductor companies have begun to embed sustainability into core operations, increasing energy efficiency and investing in sustainable manufacturing processes through new devices, yield enhancement, materials, and renewable energy sources. Yet, semiconductor manufacturing overall remains a resource-intensive sector. Powering fabs and burning perfluorocarbons (PFCs), chemicals, and gases emit notable carbon emissions[62, 63]. Water usage and chemical wastage run high and recycling manufacturing byproducts is costly and complex. **As demand for chips climbs and transistor density increases from node to node, electricity usage, water consumption, and GHGs emitted per wafer are all projected to rise.**[64]

Exhibit 13: Sustainability impact in the transition towards advanced nodes (source: Imec)[64]



Overall, the environmental impact of semiconductor manufacturing has implications on the long-term resiliency of the semiconductor supply chain. As natural disasters of the past decade have shown, resource depletion and climate change threaten the industry's business continuity, revenue growth, and workforce safety. Hence, semiconductor firms across the value chain are sharpening their focus towards sustainability.

Exhibit 14: Sustainability at each stage of the semiconductor value chain

Value chain	Company	Targets	Initiative spotlight
Design	ARM[65]	2023: 100% renewable energy across global footprint	Arm architecture as the foundation for sustainable cities, smart home, green buildings
EDA	Synopsys[66]	2024: Reduce direct GHG emissions by 25% (base year: 2018)	Enabling low-power computing through Low Power Platform built on Synopsys solutions to enable an additional 25% power reduction for SOCs over solutions currently in use
Fabless	Qualcomm[67]	2025: Reduce power consumption by 10% annually in Snapdragon Mobile Platform products	Qualcomm Taiwan Sustainability Collaboration Project—support small and medium enterprises and suppliers through sponsored installation of solar power equipment, waste heat recovery systems
Equipment	AMAT[68]	• Energy: 100% of energy from renewable energy sources in US by 2022, 100% worldwide by 2030 • Drive 30% reduction in energy consumption for semiconductor products	Industrial Waste Neutralization (IWN) water reclamation project in Austin, Texas—largest wet tool manufacturing facility; reuse treated industrial wastewater in cooling towers
Foundry	TSMC[69]	2030 UNSDG • Water usage | reduce unit water consumption by 30% (base year: 2010) • Energy efficiency: conserve 5,000 GWh between 2016-2030 • Renewable energy: renewable energy to account for 20% of energy consumption in new 3nm fabs. Long-term: fabs powered 25% by renewable energy, non-fab power consumption 100% by renewable energy • GHG: Reduce emissions per unit product by 40%	Supplier Sustainability Academy, aimed to strengthen sustainability management capabilities among Tier 1 suppliers

Value chain	Company	Targets	Initiative spotlight
IDM	Intel[70]	2030 RISE goals: • Achieve net positive water use by conserving 60B gallons of water & funding external water restoration projects • 100% renewable power across global manufacturing operations • Generate zero total waste to landfill • Increase product energy efficiency 10x	Sustainable Chemical Footprint Methodology to encourage suppliers to meet certain hazard criteria for high-volume chemicals and advance overall industry's use of green manufacturing chemicals
EMS	Foxconn[71]	2050: net zero GHG emissions Smartphone manufacturing: implementing new mold process so that < 1% of paint is wasted, thereby lowering chemical fume release; substituting traditional smartphone screen film with new carbon nanotube film that uses 80% less energy to produce	New state-of-the art, eco-friendly industrial park in Southwest China that uses wind tunnel to cool servers, leverages approximately 100% recycled steel in buildings, and integrates smart sensor-based streetlamps

TREND 3

Talent shortage

The big tech talent war continues to intensify, as the world's most skilled engineers flock to software companies and the global shortage of STEM talent persists. With strong brand equity and compensation packages, leading software players have secured top engineering talent and have hired 70% of top-tier AI specialists in the US.[72] Highly skilled computer scientists, data scientists, and electrical, mechanical, and chemical engineers have been attracted by $400K - $2M offer packages and the promise of influencing the next wave of technological innovation. Between a limited foothold in the talent pipeline and limited supply of global STEM talent, semiconductor companies struggle to attract skilled professionals needed to sustain the innovation race.

Nearly 77% of semiconductor executives agree that the industry faces a critical talent shortage.[73] Remote work has broadened the talent pool, but talent scarcity is a risk to industry growth. Fewer graduates are entering the semiconductor industry, due to either a lack awareness of the field or an uncertainty around long-term career potential when compared to other tech industries. Along with cross-border trade regulations and supply chain disruption, the talent shortage emerges as one of the top three issues facing the industry over the next three years. Initiatives are underway to recruit, retain, and develop talent—particularly diverse talent. ON Semi and TSMC are among a growing number of semiconductor companies that are beginning to build a more robust talent pipeline through investment in STEM programs. TSMC, for example, is launching a Girls in Semiconductor Tour to encourage high-school students to pursue careers in STEM and attend technical universities.[74]

TREND 4

Onshoring manufacturing capacity

In response to growing concerns around security of supply, the EU, US, and APAC have kickstarted a new wave of investment in domestic chip manufacturing.[53] Foundry market leaders warn against self-sufficiency in semiconductor production, citing the potential for increased costs and delayed technological advancement.[75] However, the ongoing chip shortage has underscored the need for diversified sourcing to enable supply chain resiliency. The EU is investing €20-30B to double chip production and increase its global share to 20%. The US is targeting $52B towards semiconductor research, design, and manufacturing.[1] The South Korean government is increasing the tax deduction for semiconductor R&D from 30% to 40% and doubling tax deduction rates for investment in new facilities.[76] Japan is funding $9B in the hope of reinvigorating its semiconductor sector and hedging against the possibility of zero-chip industry share by 2030.[77] Japan's investment in domestic semiconductor manufacturing is markedly lower. However, the nation's emphasis on developing a home-grown semiconductor industry is clear, as Japan recently declared that investment in semiconductors is a national mission, no less critical than ensuring energy and food supply for its people.[78]

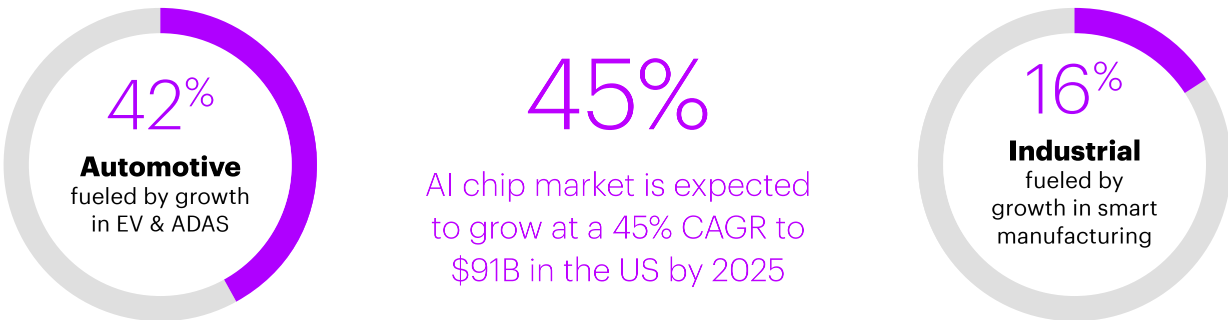
In tandem with public sector efforts, the private sector is also leading the charge for domestic capacity expansion. Semiconductor manufacturers will have commenced at least 19 new fabs by the end of 2021 and began construction on another 10 in 2022, many of which are supported by government subsidies.[79]

TREND 5

Explosion of AI, ML, Edge computing, 5G use cases

As 5G wireless technology promises faster speeds and higher capacity for an increased number of devices, the public and private sectors are figuring out the best way to deliver 5G technologies to their respective populations and consumers. The increased connectivity and wireless speeds enabled by 5G have driven the rapid development and expansion of edge computing, AI, and ML. These interconnected technologies have quickly evolved out of their prototype phases and are being readied to use at commercial scales in various industries.

Exhibit 15: AI chip market picks up steam (source: Accenture Analysis)



As AI, ML, edge computing, and 5G technologies continue to gain footing, semiconductor companies are positioning themselves to take advantage of this incredible opportunity.

IoT applications are quickly expanding utilization of AI, ML, and edge computing. IoT is a network of physical objects embedded with sensors, software, and other technologies to connect and exchange data over the internet. Semiconductor consumption for IoT endpoints is expected to grow to $63.9B US by 2023, reflecting a 16.7% CAGR. The existence of this technology and infrastructure will drive increased innovation in environments ripe for innovation and disruption. For example, rideshare apps, didn't exist until internet-enabled mobile phones did.

Exhibit 16: Cutting-edge use cases enabled by semiconductor technology (source: Accenture Analysis)

Chips are the backbone of innovation

Smart Defense
Swarming drones, intelligent weapons, satellites, and DARPA technologies

Smart Agriculture
Precision crop monitoring, farming drones, smart sensors on livestock, driverless tractors

Smart City
Smart cameras to improve traffic flow, pedestrian safety, parking, and law enforcement

Smart Retail
Smart cart automated checkout, smart shelf inventory tracking, in-store product recommendations

Smart Home
Connected home ecosystem: smoke alarms, video surveillance, lighting, appliances

Smart Mobility
Autonomous driving, automated parking, advanced, pre-collision assist, infotainment

Smart Manufacturing
Robot-assisted assembly line monitoring, predictive maintenance, production monitoring

Smart Healthcare
Pandemic compliance control monitoring, inventory tracking, precision medicine, remote patient monitoring

TREND 6

M&A activity

Horizontal integration has defined the semiconductor landscape for the past forty years. In response to steepening capital expenditures and a desire to supercharge growth, many semiconductor players opted to acquire businesses within their segment of the value chain. However, the industry is now experiencing a shift towards vertical integration, with semiconductor players venturing into neighboring stages of the value chain in a race to control the full technology stack. Intel's 2017 acquisition of Mobileye is a great example. One of the market leaders automotive-grade computer vision, Mobileye significantly accelerated Intel's entry into ADAS.

2020 was a record-setting year for semiconductor M&A activity. The industry saw an uptick in deal volume, as chipmakers aggressively moved into new areas of the value chain to enhance scale. 2020 was dubbed the year of the megadeal, with the value of agreed to and completed semiconductor M&A agreements totaling approximately $120B, compared to $32B in 2019.[84] Semiconductor companies are making big M&A bets as a strategic growth play, harnessing synergies in manufacturing capacity, product portfolio diversification, and new market entry.

Outlined below are among the industry's most high-profile mega deals, many of which are pending approval in the UK, EU, and China due to national security and monopolistic antitrust concerns.

Exhibit 17: Semiconductor mega deals of 2020-2021

JULY 2020	SEP 2020	OCT 2020	OCT 2020	FEB 2021	APR 2021	MAY 2021
$20B	$40B	$35B	$9B	$6B	$11B	$1B
Analog Devices & Maxim	**NVIDIA & ARM**	**AMD & Xilinx**	**Intel & SK Hynix**	**Renesas & Dialog**	**Marvell & Inphi**	**Qualcomm & Nuvia**
ADI announces acquisition of Maxim Integrated Products to better compete in the analog semiconductor space[137]	NVIDIA announces acquisition of ARM to become the semiconductor industry's leading competitor in edge AI computing[46]	AMD announces acquisition of Xilinx to expand into data center & cement its position in high performance computing[48]	Intel announces sale of NAND memory & storage business to SK Hynix, boosting SK Hynix' position in storage solutions[47]	Renesas announces acquisition of Dialog Semiconductor to scale IoT sector capabilities through low-power technologies[52]	Marvell completes acquisition of Inphi Corporation, catapulting its leadership in data infrastructure, 5G, and automotive[50]	Qualcomm completes acquisition of Nuvia to strengthen its CPU roadmap in both performance and power efficiency[49]

TREND 7

Ballooning venture capital investment

Until 2017, venture capital (VC) firms invested the bulk of seed capital into software startups. Historically reluctant to fund hardware startups, VC firms are now pouring billions into chip-related startups with the hope of discovering the next NVIDIA[95]. However, investment reallocation from software into hardware ventures goes deeper than this. Given the intensive costs and time required to construct a new fab, VCs are exploring the role they can play in accelerating chip design, as new chip architectures can reduce the number of chips needed for devices and minimize the need for foundries altogether. **In 2020, investors funneled more than $12B into 407 semiconductor startups, double the amount invested in 2019 and eight times the total invested in 2016**.[85] Beyond answering the call for greater semiconductor supply chain flexibility, VCs are responding to growing demand for next-generation chips that can handle AI-driven workloads. The explosion of AI/ML capabilities has created the need for new, specialized chips that can efficiently compute large workloads. Historically software-centric funds such as Battery Ventures, Bessemer Venture Partners, and Foundation Capital are actively trying to meet end-market and consumer demand through a resurgence of investment into chip startups.[86]

Exhibit 18: Glimpse into the Semiconductor Industry's Most Well-Funded Venture Startups

Startup	SambaNova Systems	Tenstorrent	groq	MYTHIC	SiFive	ambiq micro	Rockley Photonics
Headquarters	Palo Alto, CA	Toronto, CA	Mountain View, CA	Redwood City, CA	San Mateo, CA	Austin, TX	Pasadena, CA
Lead investors	SoftBank Vision Fund, intel capital, GV, Walden International, BlackRock	Eclipse, Fidelity Investments	D1 Capital Partners, Tiger Global	SoftBank, BlackRock, Hewlett Packard Enterprise, Valor Equity Partners	Qualcomm Ventures, Sutter Hill Ventures, SK hynix, Spark Capital	edbi, Kleiner Perkins	Morningside, Perscitus
Capital raised to date	**$1.1B** ($5B+ valuation)	**$235M** ($1B+ valuation)	**$362M**	**$155M**	**$191M**	**$260M**	**$207M**
Focus area	Software, hardware, and services to run AI applications	AI chips and software	High performance ML chips	Advanced AI inference for edge devices	Open-source semi technology & software automation	Mixed-signal solutions for wireless electronics	Photonics chips and custom integrated packaged products

Investment into US-based chip startups has skyrocketed, though semiconductor startups across the world are benefitting from newfound VC/CVC interest.[87] Israeli startup Valens, which focuses on uncompressed HD multimedia products for automotive and consumer electronics, is in talks to go public through a US-based SPAC.[88] With its $7B acquisition of Mellanox as an entry point into Israel's burgeoning semiconductor ecosystem, NVIDIA is on the hunt to tap into local engineering talent and grow the number of Israeli startups in its accelerator program from 279 to 1,000 in the near-future.[89] As Israel's largest private employer, Intel has invested more than $35B into Israel's semiconductor economy since 1974 and recently announced an additional $600M investment into autonomous driving R&D efforts with startups. Chinese semiconductor startups are also prone to the VC land grab effect, with Shanghai-based Enflame Technology raising nearly $280M and Beijing-based Horizon Robotics raising upwards of $750M earlier this year.[88]

3

Global semiconductor market

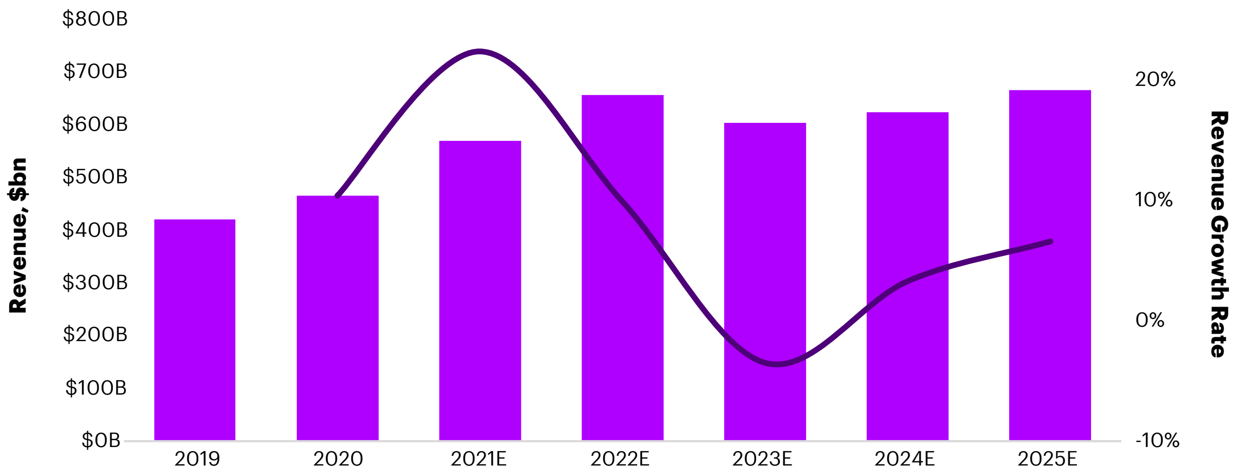
Semiconductor demand

With a $422B market size (2020), the semiconductor industry is a pervasive contributor to the global economy. Accounting for 0.5% of the $84T global GDP, semiconductor industry is economically critical and carries significantly more weight than its size suggests. **Several macroeconomic indicators, ranging from internet consumption and mobile phone usage, hinge on stability of the semiconductor value chain.**

The semiconductor industry is highly cyclical, particularly in memory, and sensitive to downstream sectors that depend on chips, such as data processing, telecommunications, and consumer electronics. Technological advances in consumer electronics dictate the lifespan and replacement cycle of many electronic goods. Think: enhanced camera quality on the iPhone 13 Pro Max or a new controller for the PS5 gaming console. Innovation breeds consumer appetite for the latest and greatest product features, which in turn, causes an upswing in demand in the semiconductor industry. When downstream sectors struggle to keep pace with demand, semiconductor companies tend to increase chip prices and invest revenues back into the business. When supply exceeds demand, either through over-production or reduced demand, semiconductor foundries lower fab capacity[90], which ultimately is passed on to customers through lower selling prices.

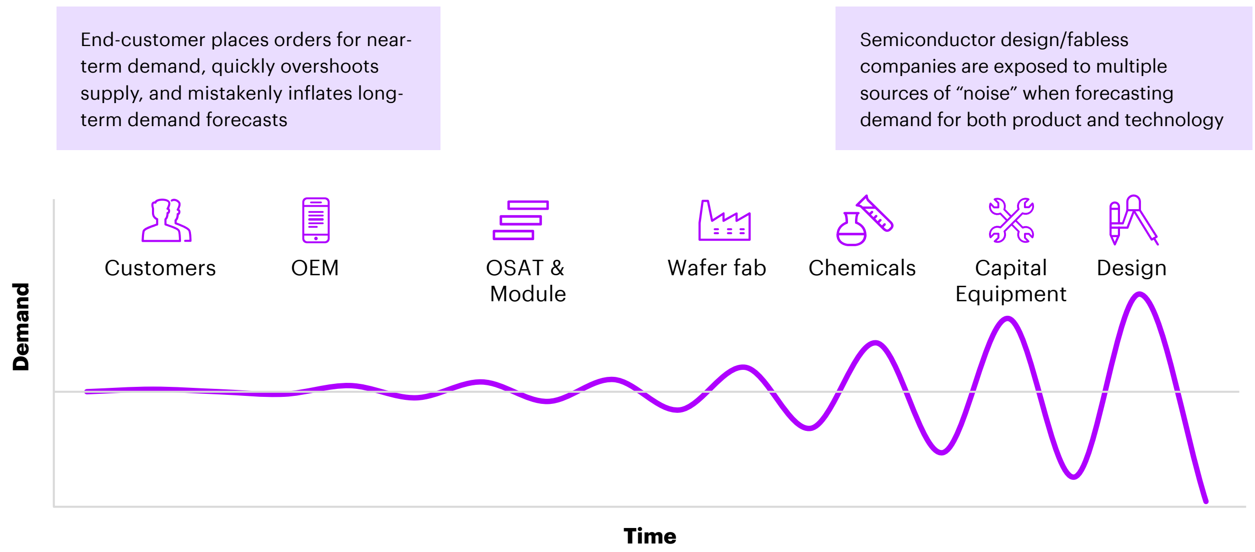
Despite a revenue decline in 2019, semiconductor industry growth has climbed over the past few years, bolstered by the commodity-like nature of generic processors and increased demand for chips in the smart, connected ecosystem. While the price of generic semiconductors has faced downward pressures, specialized semiconductor chips command price premiums. To accommodate for increased demand, semiconductor foundries and IDMs have doubled down on new fab construction. However, because of one-to-two-year lead times to build these facilities, fab capacity will remain relatively fixed in the near-term, in turn driving a surge in prices. Global semiconductor sales are projected to increase by 19.7% YoY in 2021 and by 8.8% in 2022, a figure that is 6.8% higher than recorded in 2020 when COVID-19 hit. **Semiconductor demand is expected to continue rising, at a 7.4% CAGR through 2025, particularly as chip specialization unlocks new use cases in a broader set of downstream industries.**

Exhibit 19: Semiconductor forecasted revenue and growth rate through 2025E (source: Gartner)



Forecasting semiconductor demand by end-market, is complicated by the bullwhip effect, which epitomizes the disconnect between end-market demand signal and OEM capacity requests to semiconductor manufacturers. Demand distortion begins when an end-customer places orders for near-term demand, quickly overshoots supply, and mistakenly inflates long-term demand forecasts. In reality, an increase in near-term orders does not foretell a net upside in demand in subsequent periods. However, with lengthy manufacturing lead times, OEMs tend to over-forecast to secure supply out of caution. Semiconductor capacity forecasting is further complicated by the fact that foundry process technology has often yet to be finalized for OEMs who have yet to finalize chip designs for highly customized parts. In 2021, the chip shortage extended the average lead time from order date to delivery date to nearly 52 weeks.

Exhibit 20: Bullwhip effect for semiconductor forecast



Product overview

This demand is for a range of products. Semiconductors are generally categorized into eight core product segments:

Exhibit 21: Semiconductor product segments

Product segment	Sub-segments	Description	Example	Key players
Logic	• Display drivers • FPGAs • Programmable logic devices (PLDs)	Semiconductor products that serve a general-purpose binary logic function	Display drivers for video display	• Xilinx • Intel • Samsung • Novatek • Texas Instruments
Memory	• DRAM • NAND Flash • Emerging memory	Stores retrievable electronic information (short-term and long-term)	64GB of memory in an iPhone	• Samsung • SK Hynix • Micron • KIOXIA • Western Digital • Intel • Nanya Technology
Analog	• Data converters/ switches/multiplexers • Voltage regulators/ reference	Building block used for electrical signal processing, power control, or electrical drive applications	Switches for electronic devices	• Texas Instruments • Analog Devices • Maxim Integrated • ON Semiconductor • STMicroelectronics • Renesas
Optoelectronics	• CCD image sensors • CMOS image sensors • LEDs • Photosensors • Couplers • Laser diodes	Semiconductor products in which photons induce electron flow	Light sensors for auto headlights	• Sony • Samsung • Will Semiconductor • Nichia • Osram • STMicroelectronics • Broadcom
Discrete	• Transistors • Diodes • Thyristors	Single-circuit component on chip	Transistors for circuit design	• Infineon • ON Semi • STMicroelectronics • Nexperia • Toshiba • Rohm

Product segment	Sub-segments	Description	Example	Key players
ASIC (application-specific integrated circuit)	• Discrete application/ multimedia processors • Discrete cellular baseband • Discrete GPUs • Integrated baseband/ application processors • Power management • Wireless connectivity (NFC, Wi-Fi, Bluetooth, GPS, combo) • Wired connectivity • RF front end & transceivers	Semiconductors designed for a specific end application for use by a single customer	iPhone X chip	• Qualcomm • Broadcom • Intel • NVIDIA • MediaTek • Apple • HiSilicon Technologies • Samsung • AMD • NXP • Texas Instruments • Skyworks Solutions • STMicroelectronics • Realtek • Qorvo • Infineon
Non-optical sensors	• Environmental, fingerprint, inertial, and magnetic sensors • MEMS microphones	Sensors that convert measurements of physical, chemical, or biological properties into electrical signals	Temperature sensor for nest	• Bosch • Infineon • Goertek • TDK • STMicroelectronics
Micro-components	• Digital Signal Processors (DSP) • Microcontrollers (MCU) • Microprocessors (MPU)	General-purpose ICs that can be programmed to perform specific activities	Medical diagnostic imaging	• Intel • AMD • NXP • Renesas • STMicroelectronics • Microchip Technologies • Texas Instruments • Marvell

These semiconductor chips can be split into two main groups, general purpose chips and application specific chips. Memory, analog, logic, discrete, micro components, optoelectronics, and non-optical sensors can be classified as General-Purpose chips and are commodity like in nature. The ASICs (Application-Specific Integrated Circuit) include chips with specific uses such as those needed for satellites or bitcoin.

While general purpose chips will continue to make up the bulk of semiconductor demand, the growing use of semiconductors in automobiles, home appliances, wearable devices, and IoT have spurred demand of ASICs. Between 2016-2019, the growth of general-purpose chips (7.9%) was more than double that of ASICs (3.9%). However, in 2019-2020, that trend was reversed with general purpose chips still seeing steady growth at 8.2% while ASICs grew at an accelerated pace of 15.3%. This trend looks to continue in the next few years as the growth of ASICs is forecasted to outpace that of general-purpose chips through 2023. As more and more industries seek to include semiconductor chips into their products, current semiconductor players will have to adjust their current production capacities and capabilities to meet this demand.

Exhibit 22: Semiconductor forecasted revenue and growth rate through 2025E by product segment (source: Gartner)

	General purpose	Application specific
Total semiconductor market	67.4%	32.6%
2016 - 2019 growth	7.9%	3.9%
2019 - 2020 growth	8.2%	15.3%
2021 - 2025E	3.6%	6.7%

	Memory		Opto-		Non-optical		Discrete		Logic		Micro-		Analog	
Total	27%	26.1%	8.0%	8.3%	2.0%	2.4%	5.0%	5.2%	3.0%	3.2%	18.0%	18.3%	5.0%	5.5%
2021E-25E growth	**4.1%**		**7.0%**		**7.5%**		**6.4%**		**5.1%**		**(0.5%)**		**(2.3%)**	

2019 2020

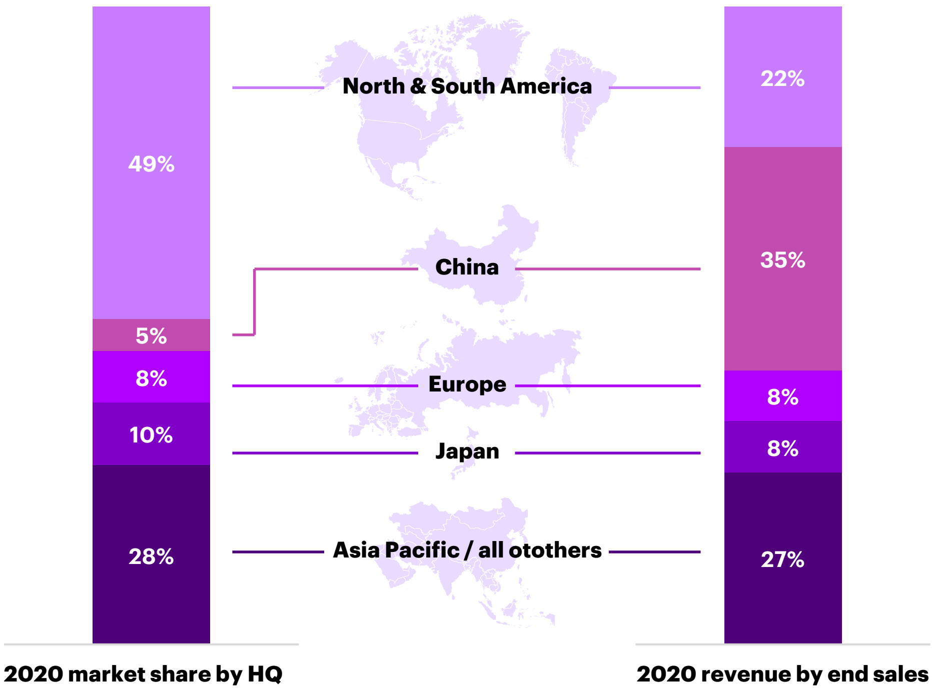
Market share by HQ geography

Globally, US-based firms dominate with the highest market share by a wide margin at 49% of the overall market. IDMs such as Intel and Micron account for three-quarters of the US market share with general purpose chips making the bulk of their revenue and ASICs only comprising of 25% of revenue. Fabless companies such as Qualcomm and Nvidia account for the remaining quarter of the US market share. For US fabless companies, the revenue profile is reversed with ASICs commanding over 75% of revenue. In 2020, ASICs experienced a 15% YOY growth compared to the 5.6% for General Purpose chips, further highlighting the diversifying needs of semiconductor chips.

South Korean and Japanese companies, with their long history in the semiconductor industry, together make up roughly 28% of the market share. IDMs dominate these markets (>90%) and the products heavily skew towards memory chips. Taiwan and China, while they are foundry powerhouses, only account for 6.4% and 5.1% of chip product development with fabless companies driving ~90% revenue. European companies round out the main global players, keeping steady at around 8% of the market.

Note: This analysis only includes the market share for semiconductor companies that design and distribute the chip (fabless/IDM). Revenue from foundry operations, such as those from TSMC or Samsung, where the company builds the chip for a fabless or IDM semiconductor company is excluded to avoid double-counting of revenue.

Exhibit 23: Semiconductor worldwide market share, sales (source: Gartner, SIA)



Demand by geography: sales worldwide

China and the rest of Asia Pacific represent the lion's share of global sales at 78% in 2020. China itself now accounts for over one-third of worldwide sales. In a true demonstration of the importance of globality, though, this includes products that end up leaving China for other country markets. Within China, over the past five years, growing household incomes and continued demand for consumer electronics has fueled the demand for semiconductor chips in Chinese products. The major American semiconductor companies pull in at least 25% of their sales from the Chinese market.[91] The U.S. is the second largest market for semiconductors in the world. Mexico is a notable destination for U.S. exports, but the demand is mostly for assembly of electronic equipment on contract, known as EMS (Electronic Manufacturing Services)[92]. Compared to the previous 5 years, the semiconductor industry is expected to grow at 7% CAGR to 2025. China and the rest of APAC is expected to outperform the industry as demand for products will continue to accelerate.

Demand by end vertical

Demand for semiconductor chips in different end industries increases with the development and production of new or enhanced downstream products (electronic goods) that incorporate electronic components ranging from more traditional applications such as data processing machines, electronic controls for engines and machinery and consumer electronics products to new applications in home appliances, medical equipment, and automobiles.

Exhibit 24: Semiconductor worldwide revenue by end vertical, sales (source: Gartner)

End vertical	Example	% of total 2020	% of total 2025E	2025 revenue projection	2021E-2025E% CAGR
Automotive	ADAS, Infotainment Chassis	8.3%	12.0%	$80.2B	12.4%
Communication	Smartphones	32.9%	31.5%	$210.3B	3.0%
Consumer	TVs, Digital Set-Top Box	10.4%	10.5%	$70.3B	2.6%
Data processing	PCs, Servers, Storage Media	37.7%	33.8%	$225.6B	1.6%
Industrial	Automation, Healthcare, Security	10.7%	12.1%	$80.7B	8.5%

Data processing

Data processing which includes computers, laptops and peripheral equipment represents the largest market segment for semiconductor chips. These ICs can be found in nearly every computer, whether it's the memory storage chip or the LEDs found in PC screens. **Demand for products in this segment experienced a spike due to the COVID-19 pandemic as employees and students worldwide were forced to shift to at-home work and study**. High-performance computing products such as PCs, laptops and tablets experienced the highest growth in a decade. Around 300M units were sold globally in 2020, up 13% from the previous year.[93] The tight supply of certain semiconductor devices, such as graphics processing units (GPUs), display drivers and DRAM, will drive up the factory ASP of PCs and Chromebooks in 2021, furthering revenue growth. However, it is expected that there will be a mild decline in 2022 and 2023.

Communications

Communications and network equipment companies create products such as cell phones, wireless infrastructure, and modems, representing the second largest market segment for semiconductor chips. **The rise in internet connectivity and increased availability of mobile devices worldwide has spurred growth in this segment. Demand for semiconductors slowed in developed economies as the 4G infrastructures matured**. This was offset by premium smartphone and other device sales and the growth of network equipment infrastructure in developing economies. However, the introduction of new 5G wireless technologies is renewing semi demand in this space. Aggressive migration from 4G to 5G, along with the high-unit growth in the smartphone market, will boost smartphone semiconductors at 24.1%, reaching $143.5B in 2021. The 5G rollout is expected to be a major driver for demand in this segment because new capabilities will be needed for 5G smartphones, high-throughput infrastructure and the IoT.[94]

Automotive

Despite some high-profile setbacks with autonomous vehicles in 2020, the automotive industry will continue to be a hotbed for semiconductor growth. Of the various market segments, auto has the highest forecast growth to 2026 at 12.4%. The auto industry is a prime example of an industry requiring increasingly sophisticated technology within their products not limited to autonomous, semiautonomous driving, and electric cars. This convergence of technical products has proved challenging as semiconductor companies race to fulfill orders for these new application specific chips for the auto industry and more traditional chips for different market segments.[95] Growth in the segment will continue to rise as automotive sales, especially electric cars, in emerging markets continue to rise.

Figure 25: Apple iPhone13 Pro board (source: Tech Insights)[96]

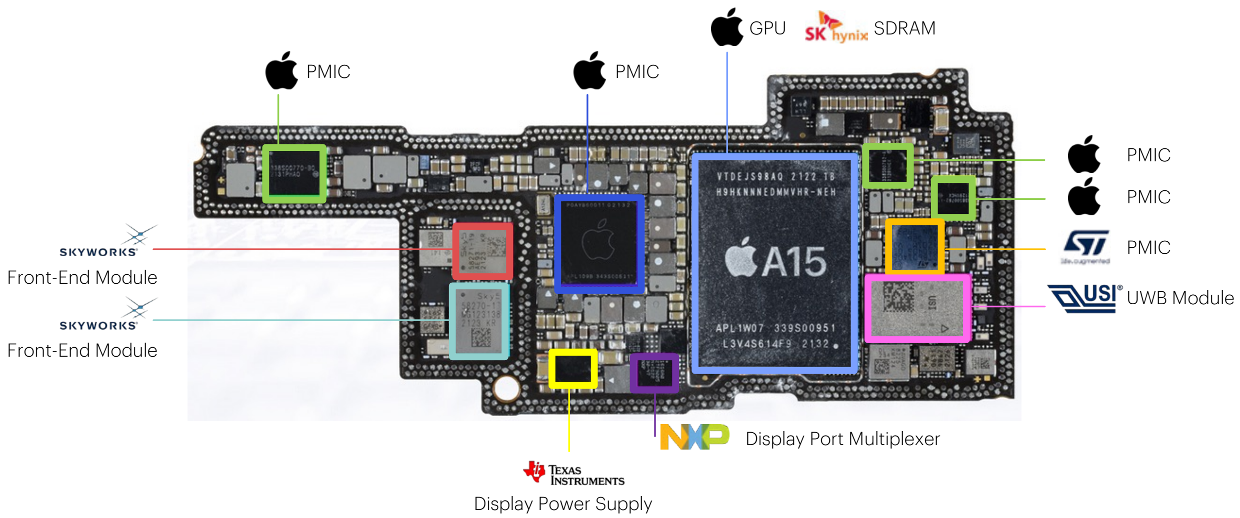
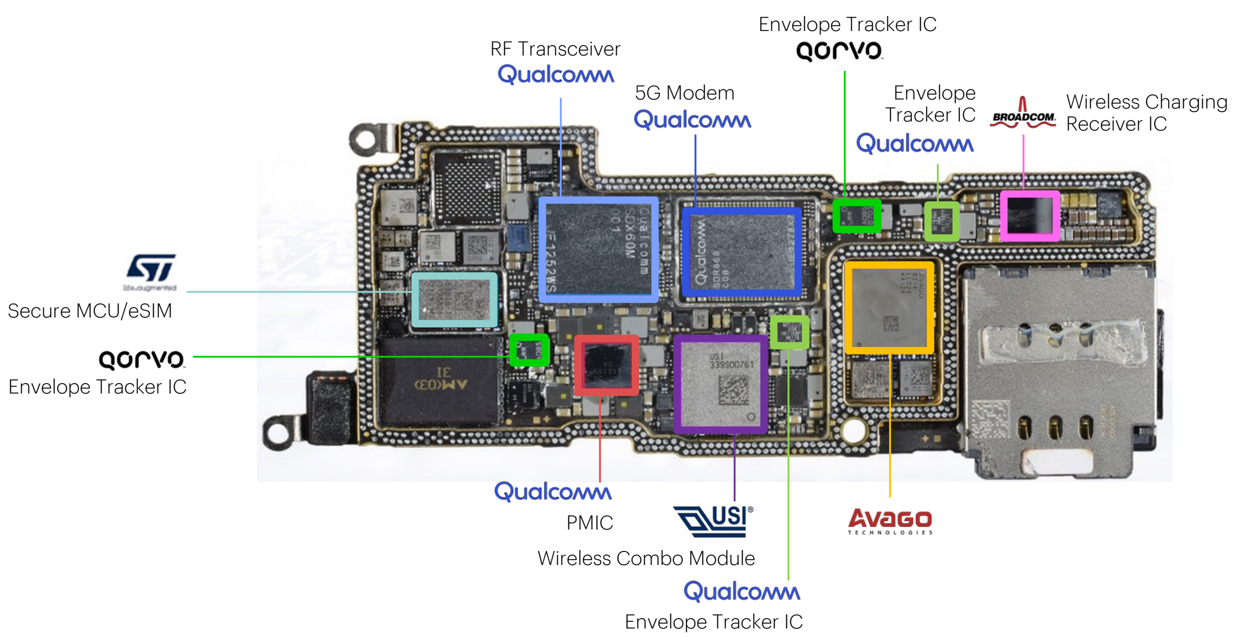


Figure 26: Apple iPhone 13 Pro board (source: Tech Insights)[96]



Global interdependence

Through assessment of an iPhone teardown, one can develop a better appreciation of the global footprint behind a single iPhone 13 pro board:

- IP cores from UK-based ARM
- Design by Apple R&D engineers across its Cupertino and Austin campuses
- EDA support from US-based Cadence, Synopsys, or Mentor Graphics
- Manufacturing of Apple's A15 Bionic SoC at TSMC's 5nm process node in Fab 18 in Taiwan
  - Equipment from various vendors, including ASML, AMAT, LAM Research, KLA, and Tokyo Electron to run 5nm process
  - Raw materials sourced from various players across South Korea, Japan, and Europe
- Manufacturing of the remainder of chips from a global mix of suppliers
  - San Diego-based Qualcomm
  - San Jose-based Broadcom/Avago
  - Greensboro, North Carolina-based Qorvo
  - Irvine-based Skyworks
  - South Korea-based SK Hynix
  - Dallas-based Texas Instruments
  - China-based USI Global
  - Switzerland-based STMicroelectronics
  - Netherlands-based NXP
- Final test and assembly by Taiwan-based Foxconn

Illustrative Set of Components for iPhone Pro Board (Not Complete)

IDM | Fabless | Equipment | OEM Assembly
Customer | Foundry | Raw Materials | Service / IP Provider

4

Economic cost of value chain disruptions

In an interconnected world, semiconductor-powered products are pervasive to our daily lives and integral to future innovation. With the advent of new edge computing, 5G, and IoT technologies, customer demand continues to climb. Today, the semiconductor industry powers $3T in the global tech economy.[97] Hence, any disruption to the semiconductor value chain precipitates a snowball effect on numerous downstream industries. The ongoing chip shortage underscores this impact, bringing the fragility of the value chain and associated costs to the forefront of the world.

Shocks to semiconductor value chain

Every industry experiences supply and demand shocks. However, **the unique nature of the semiconductor industry, with its specialized technology requirements and sprawling global footprint, means that unplanned supply and demand shocks are felt more acutely across the semiconductor value chain.** While each new shock might not make headline news, incorrect reactions to these shocks, whether its production line changes or new demand forecasts, could send the industry into a downward spiral where many industries are left without chips for its products.

Natural disasters and power outages are examples of well-documented negative supply shocks in the semiconductor industry. Lesser known, but equally as impactful negative supply shocks include cybersecurity threats, inter-region tensions, limits on raw materials, and supplier failure.

1 Natural disasters

Taiwan: In 1999, a 7.6 magnitude earthquake struck Taiwan, close to Hsin-Chu Industrial Park, home to hundreds of high-tech companies, including TSMC. While the park was spared, the resulting power failure shut down foundries, causing substantial losses as chips partway through the manufacturing process had to be discarded and plants went dark. Customers ranging from Adaptec to Motorola estimated a 10% dip in production.[98] DRAM prices spiked 600—800% due to these production cuts.[99]

Thailand: In 2011, massive floods inundated many of Thailand's industrial parks. At the time, an estimated 25% of the world's hard drives were manufactured in Thailand. Western Digital, which had many manufacturing, assembly, and test facilities in Thailand, was forced to halt much of its production and had to reallocate existing supply to storage OEMs and resellers. Prices for certain parts across the supply chain spiked 20—40%.[99]

2 Power outages

South Korea: In 2018, a fire caused a power failure for only 30 minutes at a Samsung plant, requiring all wafers in production to be discarded. This singular incident resulted in approximately $45M worth in lost production.[100]

3 Cybersecurity

Israel: In 2020, Tower Semiconductor was the target of a ransomware attack that held its servers hostage. Forced to shut down production, Tower Semiconductor paid a lofty ransom to return production to full capacity.[101]

Taiwan: In 2021, Realtek uncovered a vulnerability in its software developer kit, which could have exposed over 200 Wi-Fi and router products from 65+ vendors.[102] Had the malware attack succeeded, hackers would have gotten access to operating systems and network devices of as many as 1 million systems.[103]

4 Inter-region tensions

Japan: In 2019, Japan, which supplies nearly 90% of the world's photoresist chemicals, curbed exports to South Korea amid growing tensions between the two countries. This impacted $7B per month of Korean exports and forced South Korean semiconductor companies such as Samsung and SK Hynix to quickly find other chemical materials suppliers.[104] Prior to this, in 2018, South Korean purchases for semiconductor manufacturing materials had accounted for 20% of total imports from Japan.[105]

6

Supplier failure

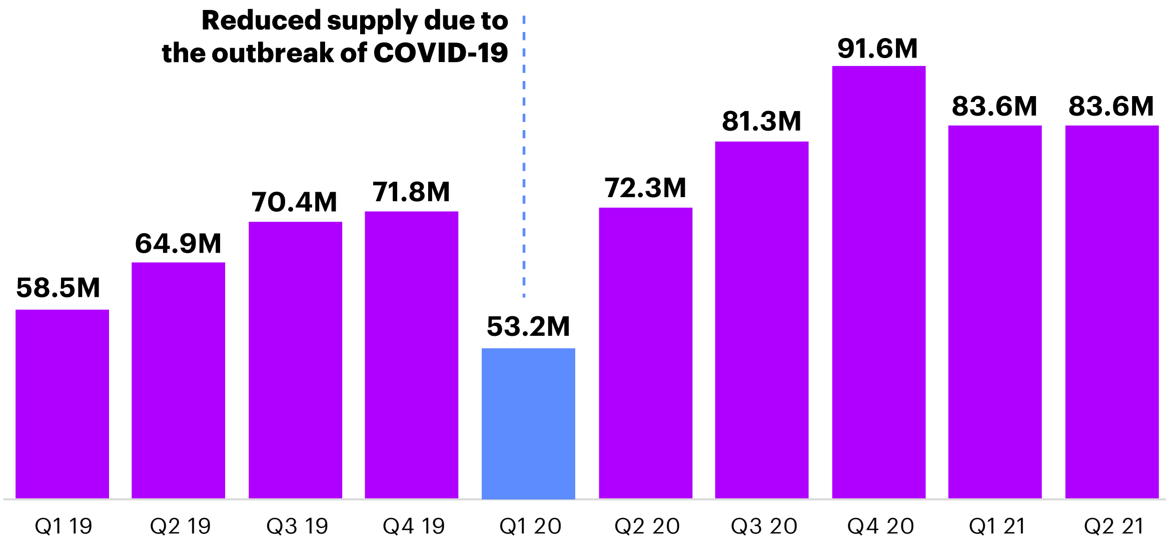
US: In 2014, Apple contracted with GT Advanced Technologies to produce new sapphire-based, scratch-resistant screens for the iPhone 6. Apple and GT planned for a $1B plant in Arizona to produce the required sapphire.[106] However, GT was unable to fulfill its obligations and declared bankruptcy shortly after construction began on the Arizona plant. To this day, Apple still does not use sapphire within its iPhone screens.[107]

In addition to the above examples, rapid changes in consumer behavior, accelerated adoption of new technologies, and regional policies have added additional uncertainty to demand, requiring semiconductor companies to quickly scale production as they hit maximum capacity while adjusting to these new and constantly changing demand signals.

Changes in consumer behavior

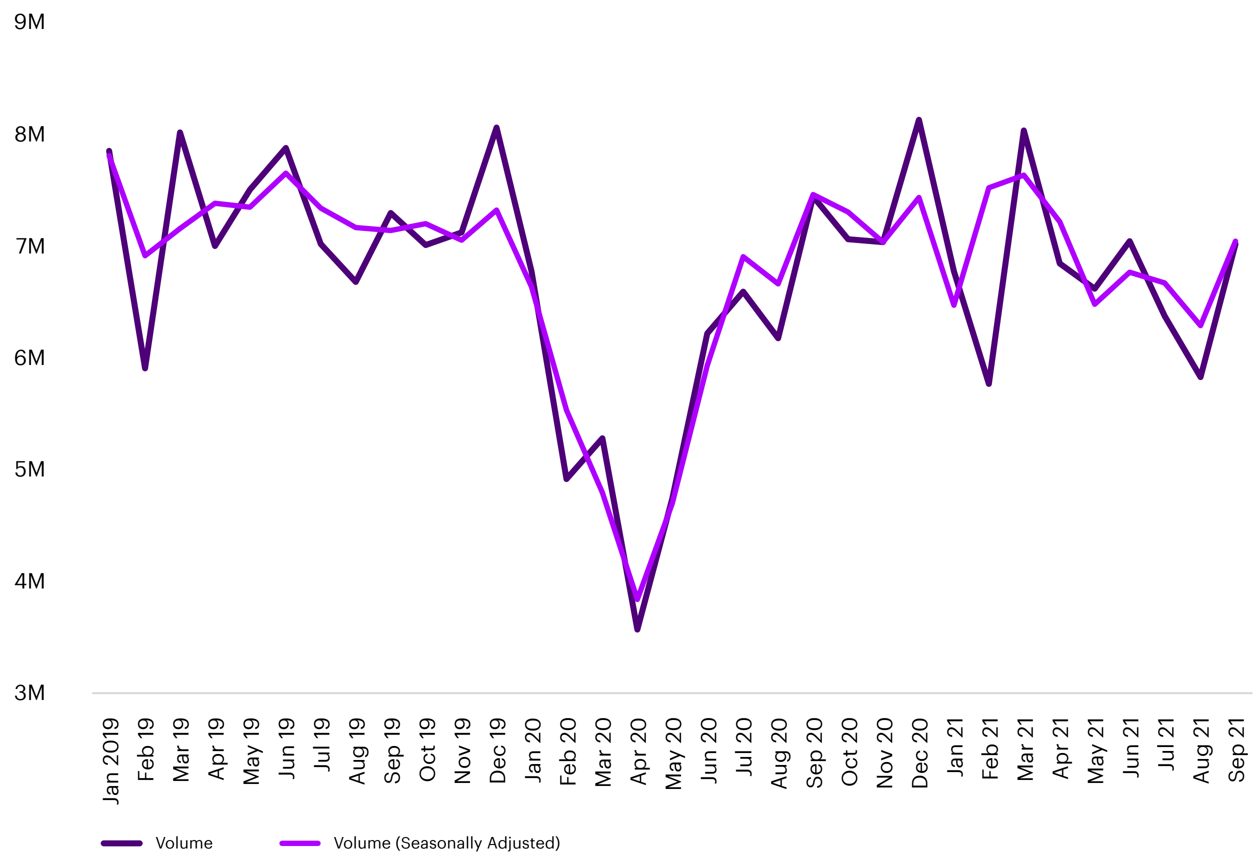
Pandemic related work-from-home guidelines and remote learning needs led to a major spike in consumer electronics spend[108]. When lockdowns first took effect, there was consensus among industry veterans and analysts that consumer spending would be diminished for a prolonged period as the global economy shrunk, just like it did after the financial crisis of 2008-2009. However, the opposite happened. Nearly two years into the COVID-19 pandemic, PC, TV, gaming consoles, and home electronics vendors are continuing to experience demand that outpaces production capacity as consumers spend on electronics that make life under quarantine more comfortable.[109]

Exhibit 26: Work-from-home guidelines induced a spike in global PC sales (source: IDC; PC includes workstations, desktops, and notebooks)



Similarly, early 2020 lockdowns led to a drastic reduction in automotive sales. Many expected depressed demand to last one-to-two years as economic activity came to a stand-still and stay at home orders negated the need for travel. But again, the opposite occurred. Once countries began to modestly relax lockdown measures, vehicle sales bounced back. Fear of COVID-19 transmission, limited testing availability, and quarantine mandates limited the populace's dependency on public transport through land, sea, and air. Consumers also channeled their desire for travel towards drivable destinations, increasing demand for cars. When auto manufacturers were unable to meet demand due to supply chain constraints, consumers turned to the used car market.

Exhibit 27: Global light vehicle sales (source: IHS Markit)



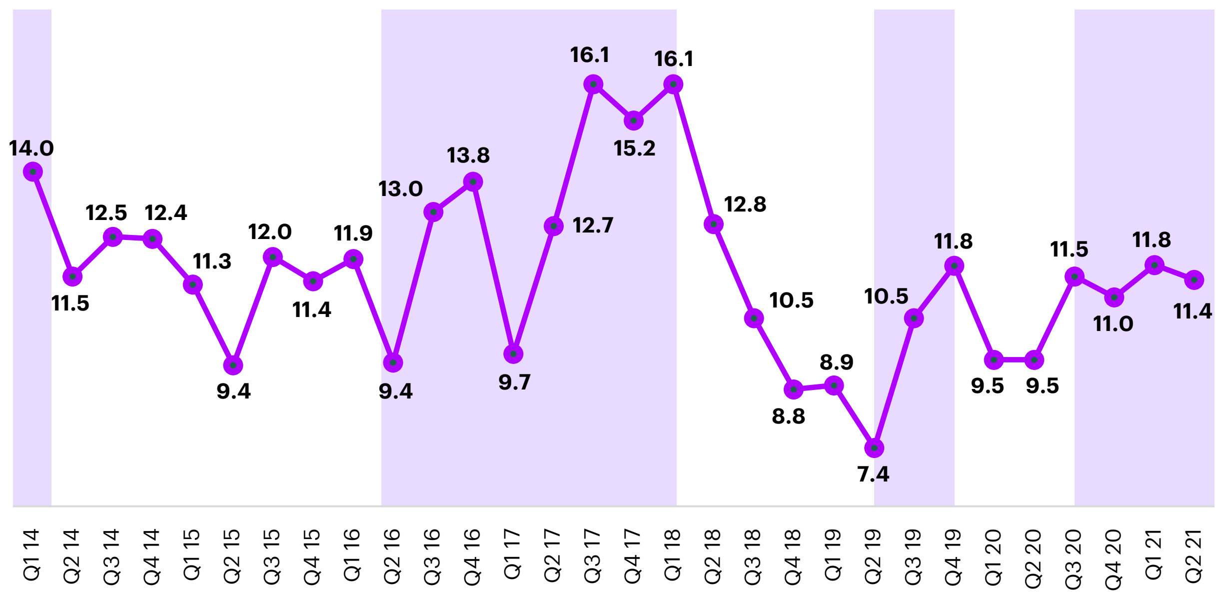
Adoption of new technologies

In 2020, rise in demand for 5G smartphones prompted telecommunications companies to accelerate 5G rollout, further constraining manufacturing capacity. Today, foundries ranging from TSMC to Samsung are boosting capital expenditures to ramp up production.[110] 5G is expected to become the innovation enabler, driving startups and tech companies to explore new possible uses for the 5G technology. This also means an increased uncertainty in demand as current forecasts have not factored potential explosive growth for killer new use case applications for 5G. Rollout delays for 5G due to COVID-19 has also exacerbated demand uncertainty.

Another example of a new technology disrupting the semiconductor value chain is the adoption of cryptocurrency. **The volatility of this market—and subsequent demand for cryptocurrency mining hardware—provides an interesting historical example of the disconnect between semiconductor manufacturers and their end consumers**. The 2017 crypto bubble saw the price of major assets such as Bitcoin and Ethereum skyrocket over 2,400%. This price spike plus a similar dynamic in transaction fees made it highly profitable to mine cryptocurrency. These potential profits plus an overall "gold rush" feeling in the market led both professional and retail miners to scour the primary and secondary markets for Bitcoin ASICs and GPUs.

Most GPU manufacturers in 2017 didn't predict this rapid spike in demand or its subsequent drop in 2018. GPUs quickly sold out in retail channels and prices on the secondary market spiked. In the future the semiconductor industry can expect to see more of these short bubbles in demand for specific products, which may contradict traditional product use cases and seasonal patterns.

Exhibit 28: Shipments of desktop discrete graphics cards in millions of units (source: Jon Peddie Research)



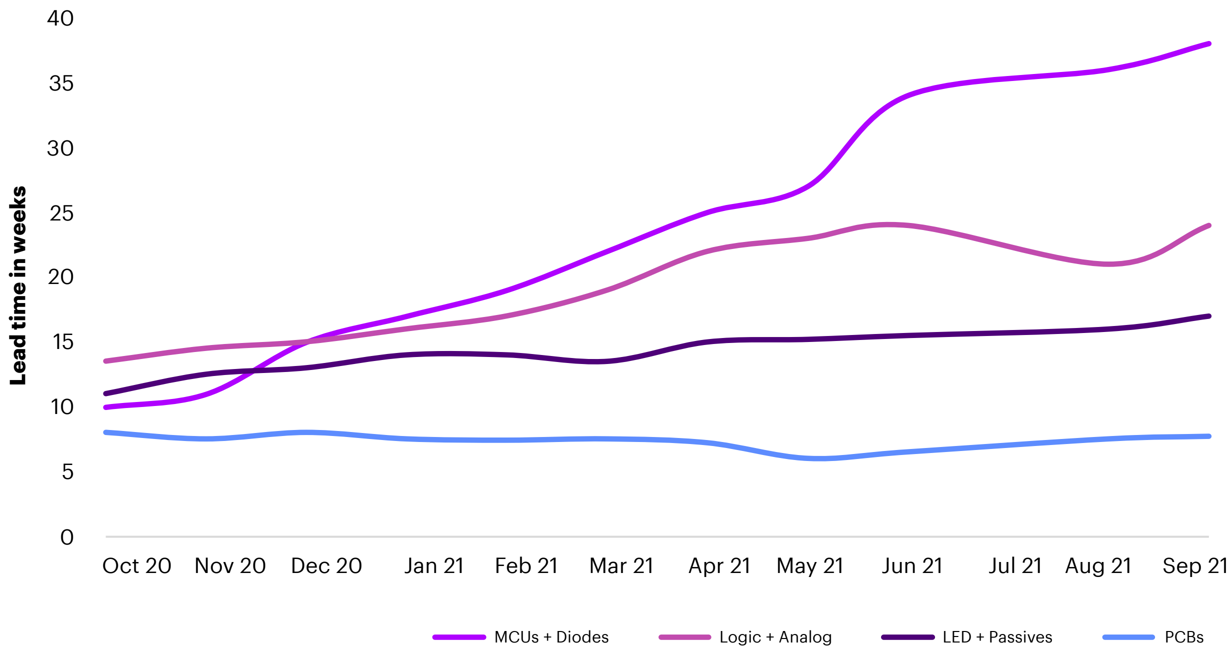
Regional policies

In 2019, US export controls policy banned Huawei from partnering with any American semiconductor company, effectively sequestering Huawei's access from leading US-based EDA vendors and equipment manufacturers. This has ultimately restricted US consumers from smartphone access, with Huawei shipping only 33M smartphones globally in Q4 2020, a drop of 41% YoY.[111]

These types of negative shocks can affect either a single point or whole sections in the value chain, all with reverberating effects across the value chain to the end user—accentuated by the global nature of this industry. **The current chip shortage is a convergence of both negative supply and demand shocks which has had ripple effects on 2nd and 3rd order industries, global GDP, and prices**.

The most immediate impact of supply chain disruption is increased lead time. When demand unexpectedly recovered in late 2020, **semiconductor lead times swung from 1 - 2 months to at least 12 months**. Some end markets were forced to halt production entirely due to non-availability of commodity silicon chips, representing single points of failure in their supply chain.

Exhibit 29: Lead time by semiconductor type (source: LevaData)



As shown in the graph above, many semiconductor components experienced a dramatic increase in lead time: MPUs, MCUs, diodes, and PLCs. These components are ubiquitous in every electronic, including automotive—and the component with the longest lead-time is often a bottleneck that prevents the end-product from reaching end-consumers.

Vulnerabilities by industry

No industry is impervious to the ongoing chip shortage. In fact, hundreds of distinct sub-industries have been deeply impacted by constrained semiconductor supply.[112] However, the automotive sector experienced disproportionately greater disruption than most other sectors, given the complexity and fragmentation of the automotive supply chain translating into relatively low purchasing power, and its high (and growing) reliance on semiconductors for its end products.

High tech industries

Chip-centric technology industries build products whose performance, quality, and user experience are dependent on the chips powering them. Smartphones, PCs, desktops, gaming consoles, data centers, and network equipment infrastructure are classic examples, all of which are projected to grow significantly with the rising wave of 5G, IoT, and AI/ML. **Because chips are integral to powering these end products, companies in these industries strongly influence design and demand for high-volume manufacturing**. Such level of influence translates to greater purchasing power, and strategic relationships with companies across the semiconductor value chain, in turn allowing high-tech companies to secure better supply allocation during times of supply constraint. In addition, semiconductor foundries invest more into high-margin, high-volume chips, which are typically used by companies in high tech industries.

Non-high tech industries

Other industries build products that are generally less compute intensive and require commodity chips in mature nodes. **Unlike technology industries, these industries often do not design their chips and use off-the-shelf semiconductor components**. They also traditionally have limited direct contact with the foundries and weaker ties to the semiconductor value chain, instead working through distributors and Tier-1 electronics makers and module assemblers.

Automotive

Today's cars contain upwards of 3,000 chips. Older generations use relatively low-cost chips to enable power steering, dashboard, speedometer, and cruise control capabilities. **As governments incentivize consumer shift from Internal Combustion Engine (ICE) to Electric Vehicles (EV), chip demand will increase due to the larger number of chips in EVs.** The rise of autonomous vehicles (AVs) will further increase demand for more advanced chips due to the high level of compute power required. Hyperscalers from Alphabet's Waymo to Tesla have begun to design their own chips in-house and work directly with foundries.

Pet tech

Unexpected downstream industries such as pet tech continue to be intensely impacted by limited chip availability. CCSI International, for example, produces electronic dog-washing booths that are dependent on semiconductors. CCSI is one of the leading employers in Garden Prairie, Illinois, with little else than a part-time office, a granary, and a few bars. The community has acutely felt the economic impact of the chip shortage, given that the chips were integral in controlling water, dispensing shampoo, counting money, and tracking time. Replacement chips are available but would prohibitively raise costs to consumers and still result in tangible delivery delays.[114, 115]

Automotive accessories

Touchscreens and GPS/Wi-Fi/Bluetooth infotainment systems are among the many interior car accessories that have been affected by the chip shortage. **Consumers are settling for lower-end models in the absence of advanced electronic features that have come to define modern vehicles.** Car manufacturer Stellantis, for example, was forced to replace its electronic dashboard with old-fashioned analogue speedometers in the Peugeot 308 model due to the chip shortage.[113]

Industrial & agriculture

From tractors to drones, forklifts, factory machines, turbines, and solar, **these applications require highly reliable and durable chips that can withstand harsh environments** (e.g., high temperature, high humidity, high pressure). A growing number of use cases involve RF chips for remote communication/control and leading-edge chips for autonomous vehicle operation.

Home appliances & office electronics

Chips used in everyday utility devices perform relatively simple tasks and require low compute power. Most rely on mature technology nodes that enable product longevity and reliability.

Spa equipment

Makers of spa equipment rely on semiconductor chips to control their equipment. However, companies such as Hot tub company Bullfrog Spa have been unable to secure temperature control touch screens produced in China and Taiwan due to the constrained semiconductor supply.[116]

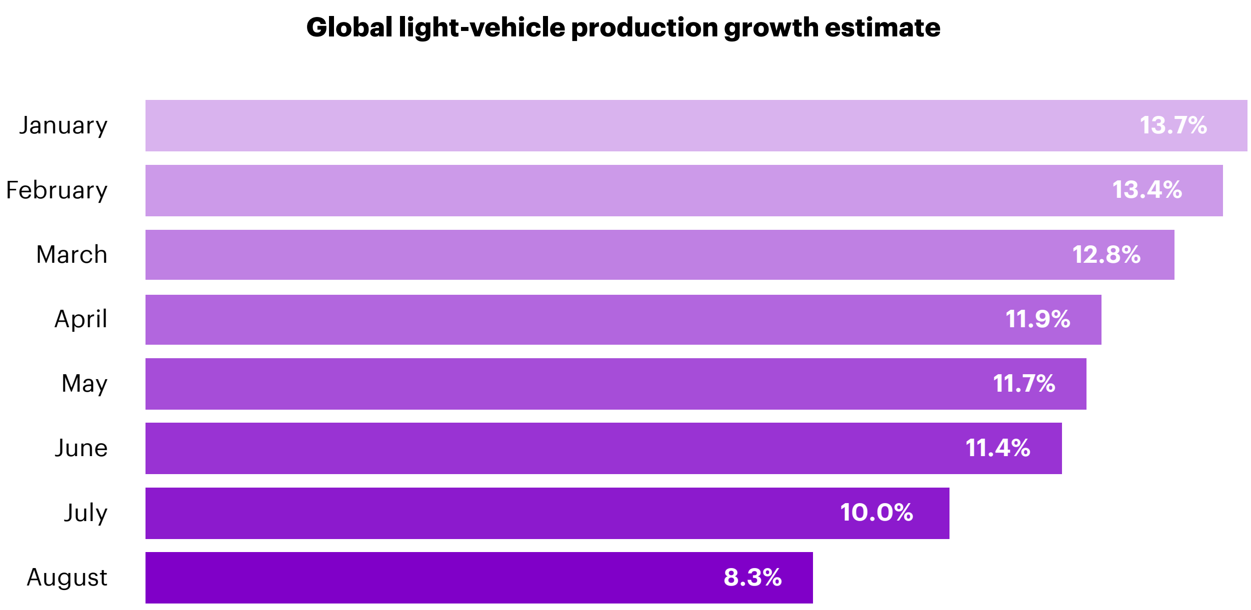
Opportunity costs

Opportunity costs differ for each stage of the semiconductor value chain. For fabless design companies, it is the inability to secure sufficient manufacturing capacity and associated revenue losses, as well as the collaboration opportunities with ecosystem partners for their products. For foundries operating at maximum capacity, opportunity costs stem from an inability to accommodate high-margin demands from smartphone, PC, and gaming end-markets. This section will focus on opportunity costs incurred by automakers, who were unable to meet unexpectedly high demand for new vehicles several months after the initial shock from COVID-19.

Typical cars contain between 1,000-3,000 chips, with each chip ranging from 5 cents (e.g., analog, sensor chip) to $150 in price (e.g., smart infotainment system). **The absence of even low-cost chips can impact core automotive functionalities and vehicle salability**. If cars are still operable despite missing chips, the chip shortage can manifest into missing support features, including side lumbar support controllers (Tesla), automatic start-stop (GM), and fuel management module (GM).[117]

At the onset of the COVID-19 pandemic, the automotive industry rushed to cancel orders for semiconductor chips under the assumption that automotive demand would plummet as people stayed indoors and minimized travel due to stay-at-home guidelines. Consumer electronics companies swooped in, capitalizing on excess foundry capacity amid rising demand for PCs, smartphones, and gaming consoles. Soon after, consumer demand for automotive picked up, but automakers quickly learned that chip supply had gone dry. Eventually, many car manufacturers halted production or sold cars with missing features.

Exhibit 30: Steadily declining automotive production projections (source: JPMorgan, IHS Markit, Bloomberg)



Impacted by the semiconductor shortage, global automotive sales in 2021 are projected to decline by several hundred billion dollars. In the US alone, Ford is projected to lose $1.5B in earnings and GM between $1.5 and 2B.[118] **On a global scale, the chip shortage is expected to hit 10.8% or 7.7M of 71.4M in lost automotive sales**. At an ASP of $40,000, this results in $308B in lost sales. Assuming these 7.7M cars sit idle in parking lots as carmakers wait for chip availability and incur 20% depreciation costs within the first 12 months, the industry will incur additional opportunity costs of $62B. Thus, total opportunity cost to global automakers in 2021 is about $370B. This twelve-month timeline is within the projected duration of the chip shortage, though some industry experts caution an even slower chip capacity recovery.

Exhibit 31: Impact of chip shortage on automotive

10.8% OR 7.7M
of 71.4M in lost automotive sales

at an ASP of $40K, this translates to
$308B
in lost automotive sales

7.7M
cars sit idle in lots, incurring...

20%
depreciation in 12 months, leading to ...

$62B
in additional opportunity costs...

10.8% OR 7.7M
of 71.4M in lost automotive sales

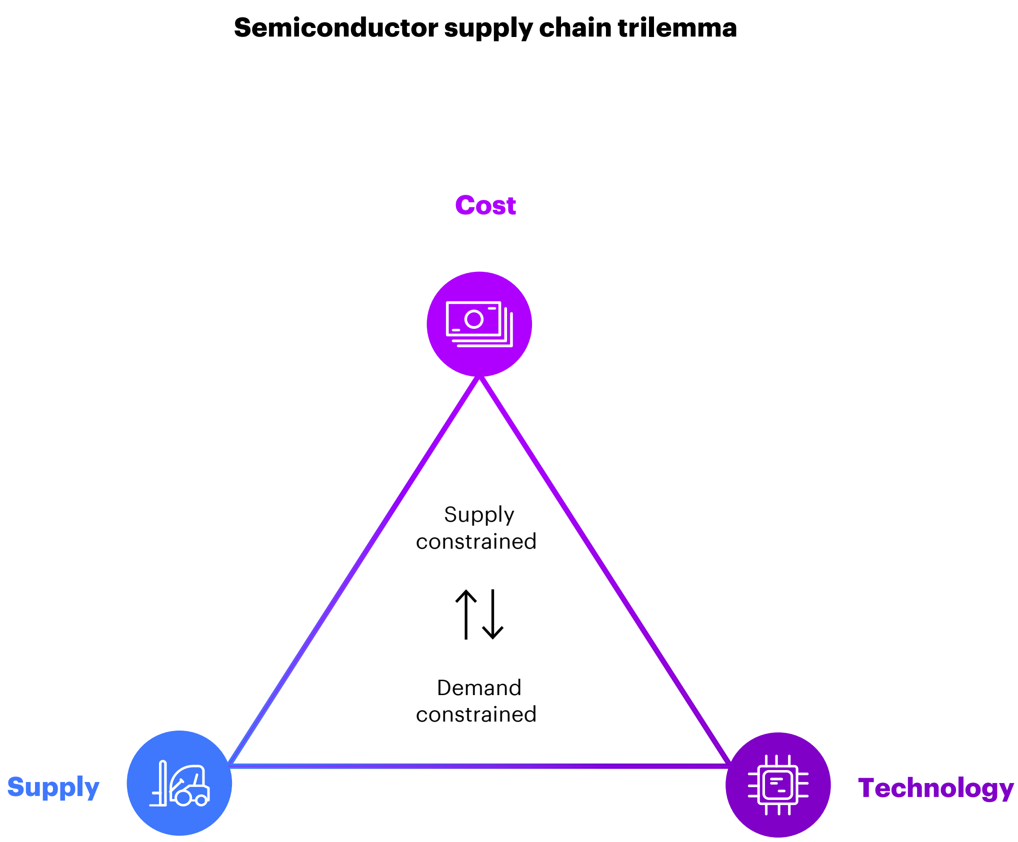
$370B
in total opportunity costs for global automotive sector

Automotive chip designers also incurred notable opportunity costs. Automotive chips accounted for 9.6% of total global chip supply and the ongoing chip shortage caused the 2020 auto chip sales to dip by 16% relative to initial projections. As foundries replaced automotive chip orders with higher margin PC, smartphone, and gaming chip orders, automotive chip designers were unable to secure foundry capacity and incurred a $6.6B opportunity cost. This positively benefitted foundries, who were awarded with higher total sales when replacing lower margin automotive chips with higher margin, compute-intensive chips.

Associated with automakers' inability to sell unfinished cars is lost revenue from regular maintenance, oil change, gas consumption, and other expenditures related to vehicle service operations—2nd and 3rd order effects from the chip shortage.

The sustainability agenda has also been impacted by the chip shortage. In August 2020, President Biden announced an executive order calling for 50% of new cars sold by 2030 to be EVs or plug-in hybrids. **However, given current EV market share and semiconductor-related delays in EV production, carmakers risk falling short of this deadline.**[119]

Exhibit 32: Semiconductor supply chain trilemma (source: Qualcomm). PPA = power, performance, area.



The semiconductor industry is complicated by the fact that only two of three levers—cost, supply, technological innovation—can co-exist at any point in time. Known as the semiconductor trilemma, this phenomenon explains the ever-present tradeoffs that push and pull against supply chain decision makers across the value chain. For example, semiconductor companies can minimize costs and flex production up or down through lean, agile operations. However, this comes at the expense of technological innovation—be it power, performance, or area gains realized at the next node or efficiencies extracted at existing nodes—given the time and investment required to push the envelope of innovation.

Levers to balance	Outcomes
Scenario 1 Maintain low cost & ensure sufficient supply	Progression towards next advanced node is stalled, intensifying the threat that competitors may leapfrog in cutting-edge technological capabilities
Scenario 2 Maintain low cost & drive technological innovation	Potential for inadequate supply, translating into inability to meet end-market demand for products
Scenario 3 Ensure sufficient supply & drive technological innovation	Difficulty managing costs, placing a strain on the business and sustainability of operations

Depending on their market positioning, semiconductor companies may choose to optimize for any two given vertices in the trilemma, placing these companies into contact with one of two fates:

Demand-constrained scenario: With adequate supply, semiconductor companies may choose to optimize for cost and innovation. To mitigate risk of excess and obsolescence, semiconductor leaders will opt to keep a lean inventory profile. Factories will get the signal to manufacture, build, and assemble less inventory, reducing the need for inventory write-off. This increases a company's exposure to fluctuations in demand. However, the risk is worth the reward, as semiconductor companies are in a better position to focus R&D towards leading node process technology, advanced packaging solutions, and investments that enable continued momentum in line with Moore's Law.

Supply-constrained scenario: When supply is constrained, semiconductor companies scramble to replenish inventory. This often takes shape in the form of new supplier agreements, wherein semiconductor companies are liable for buying established given supply quantities within a pre-defined schedule. As semiconductor companies struggle to keep pace with demand, prices surge, which in turn increases pass-through customers to end customers. In the absence of supply and rising costs, semiconductor companies are not in a favorable position to invest in technological breakthroughs.

In either scenario, semiconductor companies who minimize risk are those who: (1) shape flexible product roadmaps, perhaps by assembling products in common package types or testing through common equipment, (2) maintain process portability through multi-sourcing strategy (e.g., multiple foundries run at more than one node), (3) use a combination of mature and advanced node in product development, and (4) develop specialized Centers of Excellence in strategically located geographic clusters.

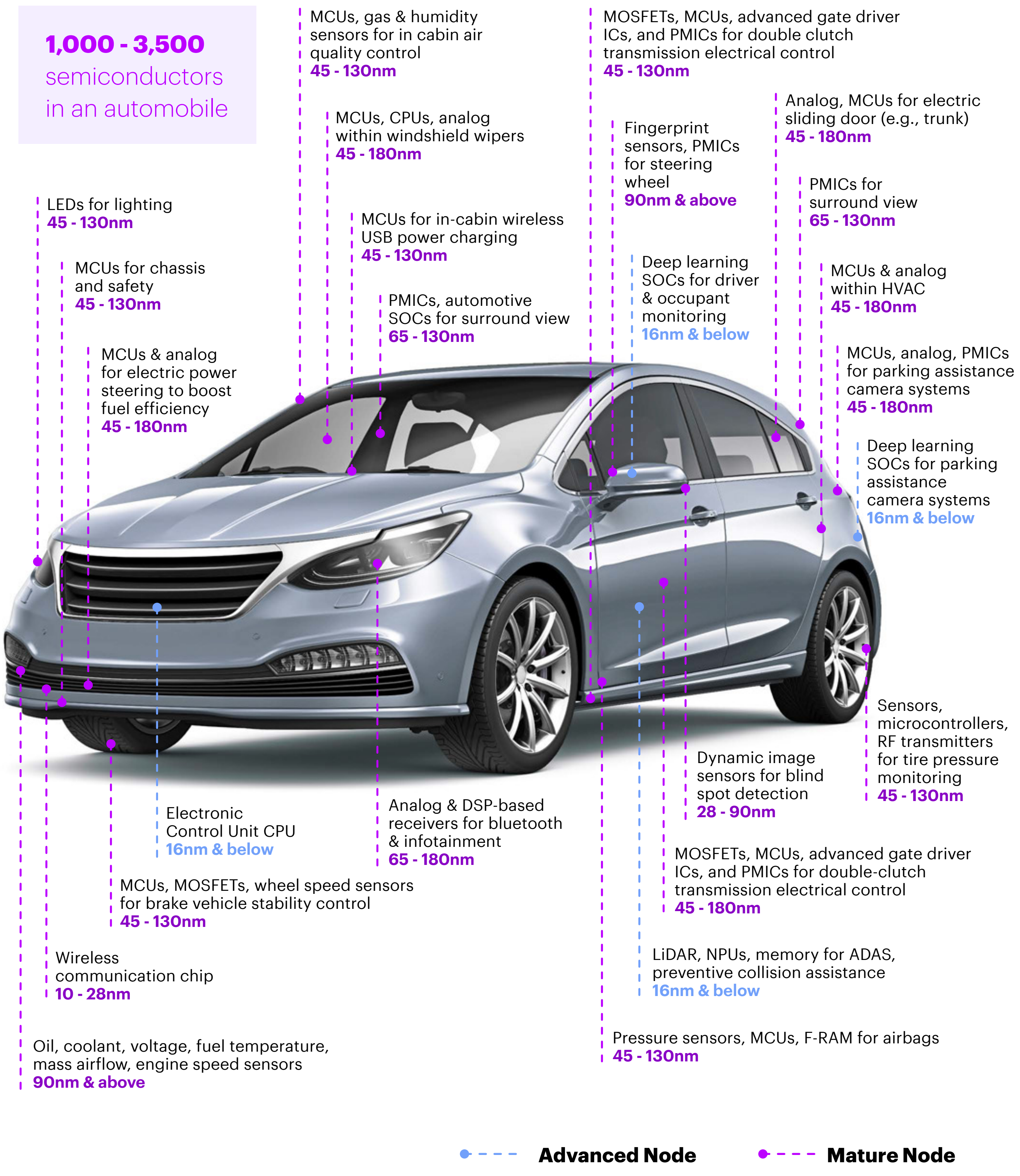
Investment in advanced & mature nodes

Semiconductor manufacturing can be defined by either leading node or trailing node process technology. Chips produced at the leading, or advanced, nodes are smaller in size. The smaller the size, the smaller the transistors, and the faster and more power-efficient the chip. Hence, chips developed on leading nodes are used to power state-of-the-art workloads that enable cutting-edge 5G, IoT, edge AI, and cloud capabilities. These chips enable faster object detection in autonomous vehicles, better mobile phone battery life, and lightning speed laptop functionality. On the other hand, trailing, or mature, nodes surpass leading nodes in reliability and price and are thus critical in production of large-scale devices (e.g., automobiles, home appliances, medical monitoring apparatuses, construction equipment, TVs). **Despite this delineation, every modern electronic requires a combination of both leading and trailing node processors to function properly**.

Exhibit 33: Progression of mature and advanced nodes over time

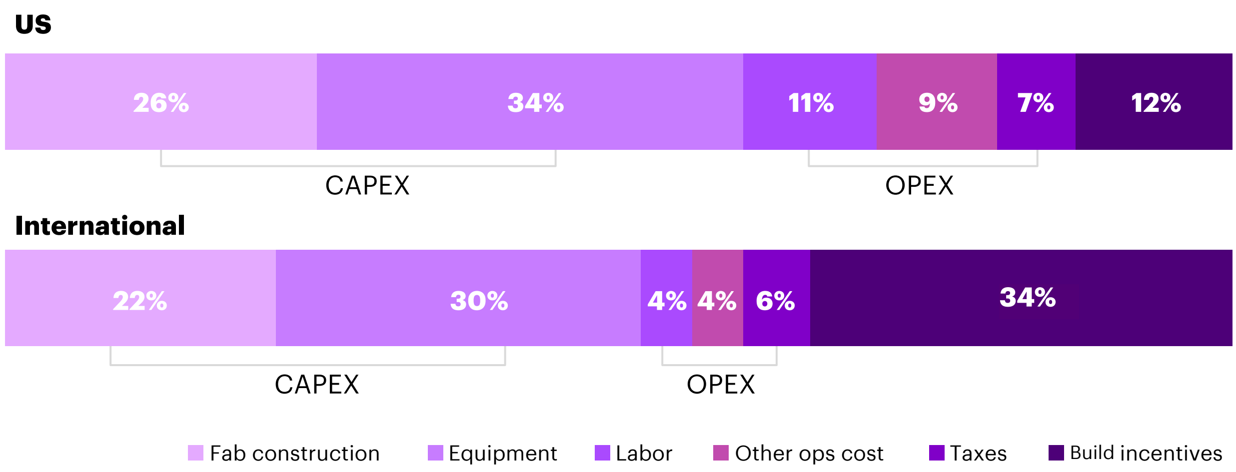
2004 - 2007	2007 - 2009	2009 - 2012	2012 - 2015	2015 - 2018	2019 - 2021	2021+
0.13um – 65nm	32nm	32nm – 22nm	22nm – 14nm	14nm – 7nm	5nm	3ntm
Complex mobile with Internet access Transition from desktop to laptop	Logic emerged as largest component Reduced investment per employee	Growth in professional PC market Emergence of alternate devices reduces growth in consumer PC Strong growth in smartphone sales & decline sales of traditional mobile Tier 1 auto suppliers continued to benefit from growth of electronics in cars	Decline in PC production Saturation in the premium smartphone market as growth tilts toward lower-priced models Move towards fab-lite model Paradigm shift to in-house chips, fragmenting mobile market into custom & commodity SoCs	Smartphone growth continued but PC & tablet market sluggish New manufacturing technologies, marked shifts in demand patterns, and greater price pressures cutting into bottom line Rise of Chinese chip companies	Demand for lower power consumption in 5G mobile impels chipmakers to move to lower process nodes Capacity expansions required due to higher demand & rising 5G expectations	Increased demand in ultra dense chips with emergence of new technologies New tech on the rise: distributed ledger tech, AI, AR/VR, quantum computing Chip segmentation increases with AI & ADAS ER and IoT devices—backbone of future technology

Exhibit 34: Subset of advanced & mature nodes in an automobile



The number of foundries and IDMs that manufacture at advanced nodes has declined significantly over time. Nearly decades ago, roughly 20 semiconductor companies produced chips at advanced nodes. But as CapEx skyrocketed and technical know-how became harder to acquire, fewer players survived in the advanced node space.

Exhibit 35: Cost breakdown for semiconductor fab



As a result, GlobalFoundries, ST, Sony, Infineon, Freescale, and NXP all strategically opted to build on success achieved at mature nodes, rather than sustain investment in leading node technology. Today, only three firms successfully compete at manufacturing advanced nodes: TSMC, Samsung, and Intel. While the industry has experienced rapid growth in advanced nodes, growth in mature nodes has increased in the low single-digits, largely due to equipment depreciation schedules and fab re-tooling timelines.

Exhibit 36: Fab re-tooling timeline

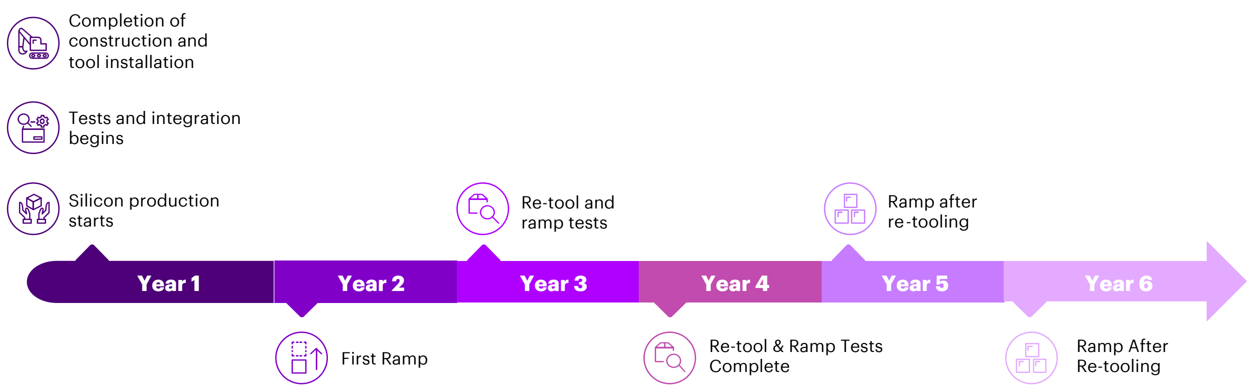


Exhibit 37: Growth in foundry capacity by node (source: Gartner)

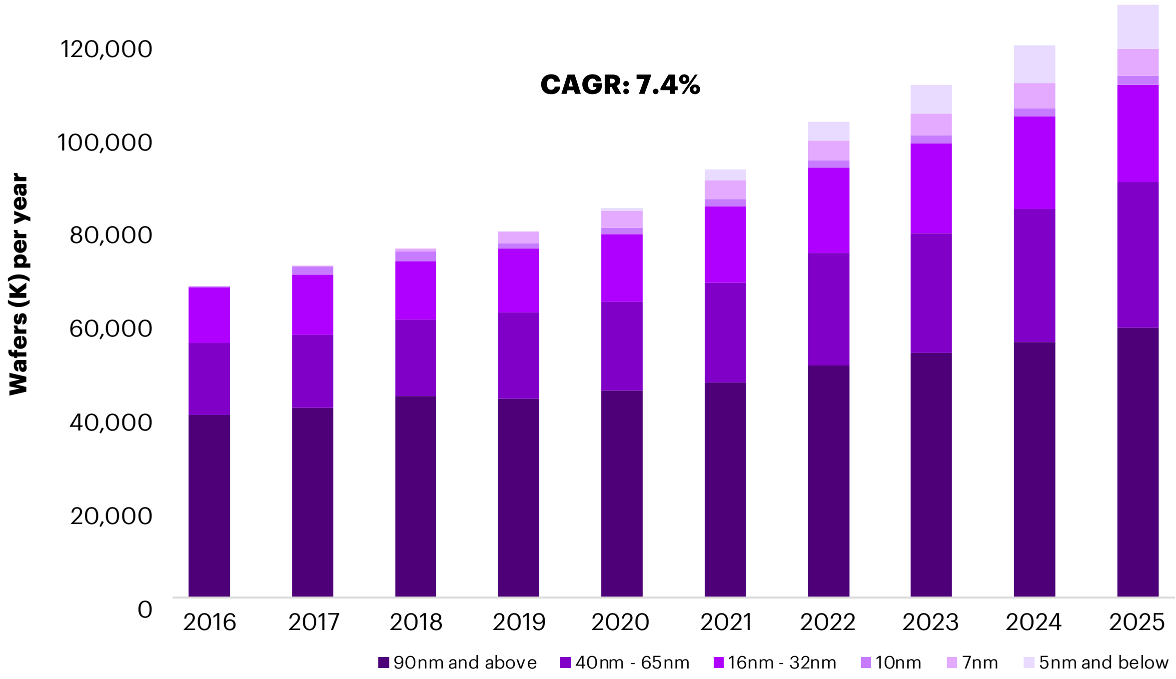
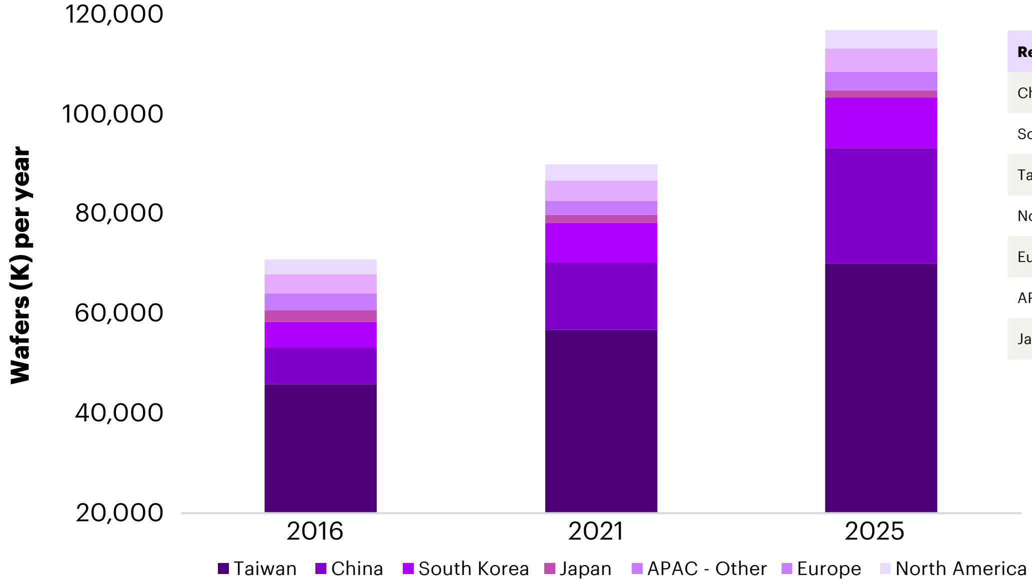


Exhibit 38: Growth in foundry capacity by region (source: Gartner)



Region/Country	CAGR %
China	13.7%
South Korea	7.8%
Taiwan	7.6%
North America	2.4%
Europe	2.2%
APAC - Other	1.5%
Japan	5.1%

Throughout the chip shortage, companies that invested in leading node technologies maintained significant competitive advantage. Many trailing node-dependent end markets, such as automotive, misjudged demand sensors and underestimated lead times. Key trailing node semiconductors, including CMOS image sensors, display driver ICs, flash memory controllers, microcontrollers, power MOSFETs, and PMICs, continue to be in short supply. In fact, trailing node capacity remains constricted across the board. Switching foundries in the hopes of gaining additional chip manufacturing capacity is not feasible, and can take several years, given the many design iteration cycles that are needed to guarantee functionality and manufacturability.

Exhibit 39: TSMC capacity utilization trend by nodes (source: TSMC)

Capacity utilization	2021	2022	2023	2024	2025
3nm			Tight	Tight	Tight
5nm	Tight	Tight	Very tight	Very tight	Tight
7nm/6nm	Tight	Very tight	Tight	Tight	Available
16nm/12nm	Tight	Tight	Tight	Tight	Tight
28nm/22nm	Tight	Very tight	Very tight	Very tight	Tight
40nm	Tight	Very tight	Very tight	Very tight	Tight
65nm	Tight	Very tight	Tight	Very tight	Very tight
90nm	Tight	Very tight	Very tight	Very tight	Very tight
0.13um	Tight	Tight	Tight	Tight	Tight
0.18um	Tight	Tight	Tight	Tight	Tight
≥ 0.25um	Tight	Available	Available	Available	Available

Nevertheless, the industry is doubling down on investment in leading node fabs to meet booming demand for smart, connected products. New US-based Intel, TSMC, and Samsung fabs will all focus on 10nm, 7nm, and 5nm leading node technologies, respectively.[121] There is a risk that the leading nodes of today are likely to be trailing nodes of the future. However, investment in trailing node technologies is complicated by equipment depreciation and government subsidies. End markets with particularly lengthy product lifecycles like automotive will need to consider accelerating their node transitions or work with ecosystem partners to invest in advanced packaging innovation in the absence of securing desired foundry capacity.

Switching costs

Material financial, relational, and opportunity switching costs are associated with a change in a semiconductor company's supplier base. Consider two key scenarios that involve switching: foundries switching raw materials suppliers and fabless companies switching foundries.

Foundries switching raw materials suppliers

When a foundry decides to explore the switch from supplier A to supplier B, the process starts with a thorough research program. The foundry's research department will first assess material specs provided by the new supplier to ensure that the raw materials from the new supplier meet the specifications required for the foundry's manufacturing operations. Once material specs are validated in small batches of wafers, the foundry will test the material in a low-volume production pilot. The pilot is a critical discovery opportunity that will likely lead to adjustments in downstream processes. One test iteration can take 4 - 6 months, potentially longer, depending on node complexity and degree of divergence between supplier A and B material specs. At least four iterations are needed before a new supplier is fully validated and integrated into a foundry's supplier network. Within each cycle of raw material validation, thorough analysis is performed on the impact of the new material on all chip designs manufactured in that foundry. If chip design integrity, reliability, and overall yield are maintained, the foundry will move forward with the switch. Chips used in mission critical military, medical, and automotive applications have stringent chip reliability requirements that result in additional temperature, pressure, and humidity reliability tests.

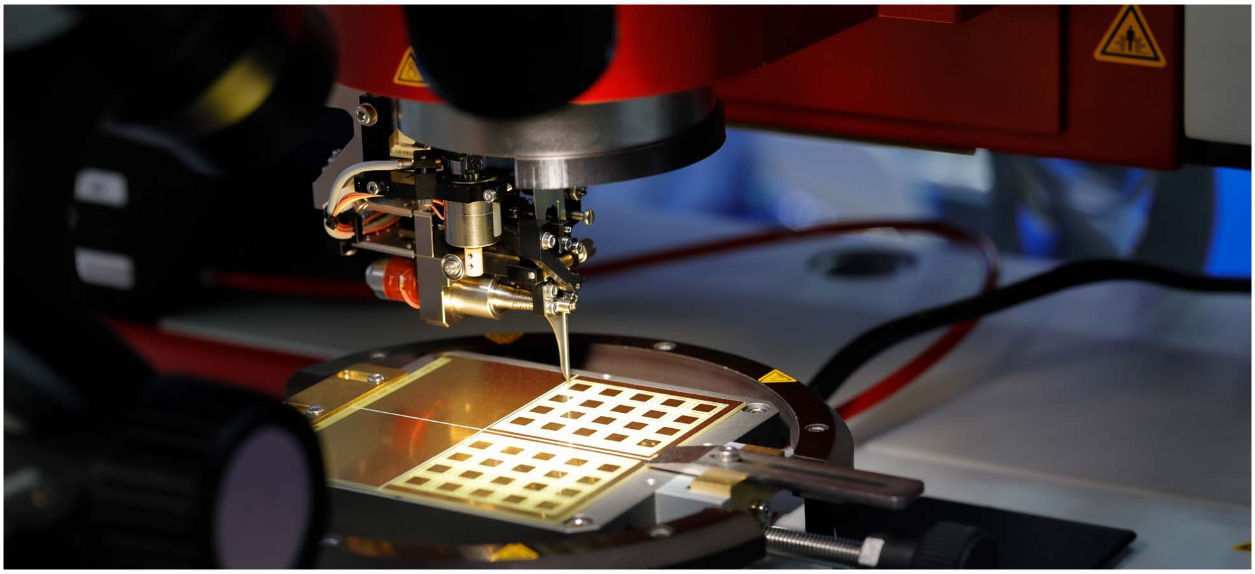
All in all, **supplier switching may take at least 2 – 3 years and command significant costs**, particularly with purchase of test equipment and execution of multiple iterations of test wafers. Switching suppliers can generate significant benefits: lower raw materials costs, enhanced supply predictability, and strengthened supplier diversification. **However, a foundry must compare these benefits with the opportunity cost of innovative work that the foundry's R&D team could have been driving in lieu of assessing the impact of switching materials suppliers**. Given how complex it is for a foundry to switch suppliers, one can expect a similar level of complexity associated with starting a greenfield fab from zero. In a situation where a greenfield fab is in a location with no existing infrastructure to support storage and delivery of raw materials or specialty chemicals, additional hurdles exist. These include the need for coordination with local authorities on safety and environmental laws, setting up logistical plans with the suppliers, and ensuring the specialty workforce is available locally. These steps, combined with the research and validation part of the supplier switching described in the prior paragraph, contribute to the extended lag time (e.g., >2 years) needed to get a new fab facility up and running.

Fabless companies switching foundries

Fabless design companies can reduce manufacturing risk by having multiple foundry partners. However, different foundries have different manufacturing processes, which are coded as design rules in each foundry's unique process design kits (PDK). For example, TSMC's PDK differs markedly from GlobalFoundries' PDK. This is because foundry IP is the most closely guarded asset a foundry has. If a fabless firm is first to market with a given chip design, it may have influence over the foundry's PDK. But if the fabless firm is a follower, it will rework its designs with the support of EDA vendors to adhere to a foundry's design rules while also ensuring the design is functional and manufacturable.

A fabless company must run several prototype wafer fabrications, with significant mask/reticle, wafer, and test costs. A design can have 70+ masks and each prototype cycle can involve 50+ wafers, each wafer containing several hundred chips that must be tested for performance validation. One prototype cycle can take 4 - 6 months to complete and cost several million dollars. All in all, when a fabless design company chooses to engage with a new foundry partner, the process of porting one chip design from foundry A to foundry B may take many years.

When a foundry shares the same manufacturing process across multiple fabs, a fabless company has more flexibility as to where chips can be manufactured. A local fab may be chosen to facilitate seamless collaboration and inspection. Contrarily, a fab closer to end customers may be chosen to reduce shipping time and costs.



Geographic specialization

An industry as capital-intensive as semiconductor is prone to regional disaggregation and geographic specialization.

Advantages	Disadvantages
• **Tap into existing suppliers, local talent, and well-developed infrastructure:** Roads, charging/fueling stations, electricity, and talent are all foundational building blocks to entering the semiconductor industry—all of which require considerable upfront investment. • **Capitalize on industry-academia interlock:** Semiconductor hubs ranging from Silicon Valley to Austin have blossomed in large part due to proximity to world-class research institutions UC Berkeley, Stanford, UT Austin, and others. Without industry sponsorship of academic programs and internships, the semiconductor industry would have no talent pipeline and no employee base. • **Cater to domestic consumer need:** As shown by European semiconductor companies, proximity to domestic end consumers in automotive and industrial enables these companies to customize products to domestic consumption needs.	• Vulnerability to natural disaster, cyberattack, social and political instability, and sudden regulatory changes. • Skillset shortage in a geography's non-focus areas of the semiconductor value chain. • R&D activity and academic collaboration require time, effort, and resources to develop from scratch. • Cross-border transport of physical assets introduces logistical challenges, costs, and lag time, requiring careful planning and execution to avoid equipment damage and schedule delay.

Agglomeration

Semiconductor companies tend to co-locate in geographic clusters to leverage existing infrastructures, tap into local talent pools, and promote cross-collaboration to foster innovation. Co-location helps achieve economies of scale and network effects, where any additional influx of semiconductor business or talent to an existing ecosystem improves its overall quality and productivity level. Listed below are key regions with uniquely high concentration of semiconductor companies.

North America

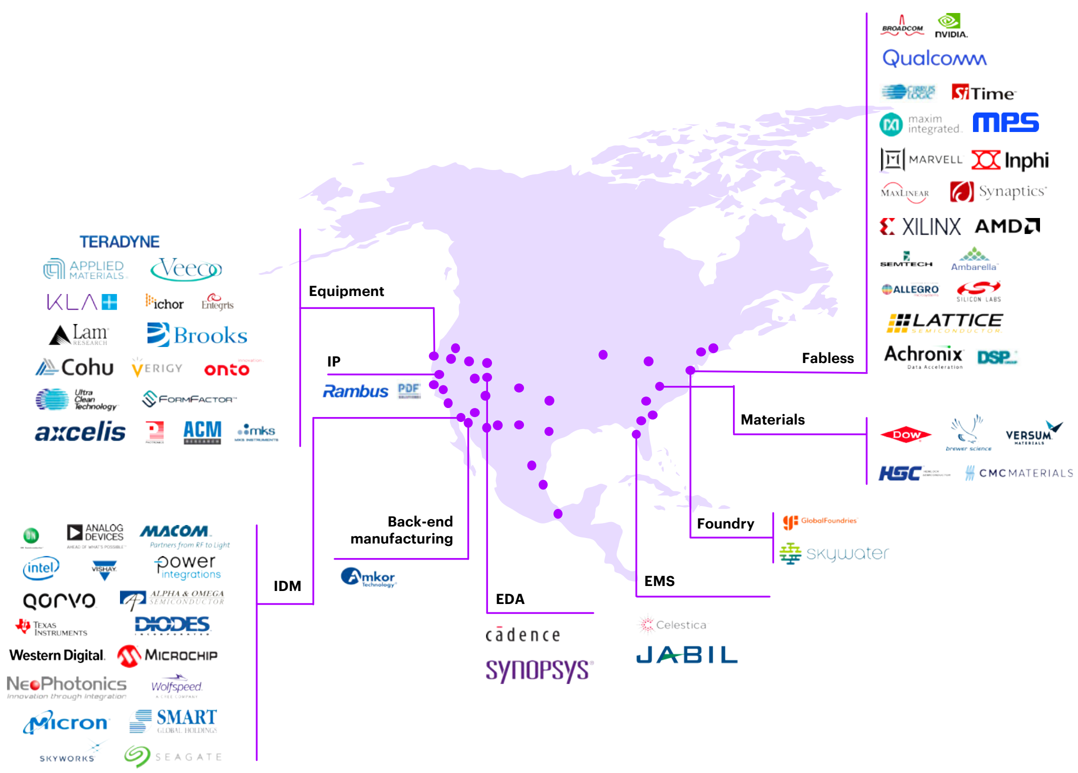
Silicon Valley

Silicon Valley is the birthplace of semiconductor industry, with a large pool of hardware and software engineering talent and proximity to world-renowned academic research institutions (e.g., Stanford, UC Berkeley) and venture capital. Today's Silicon Valley is known as a software innovation mecca. However, Silicon Valley's origins date back to early-stage semiconductor R&D and commercialization during the advent of the field.

Austin

Austin has become a burgeoning semiconductor hub, due to the city's low startup costs, business friendly regulations, and access to high-quality research institutions (e.g., University of Texas). Leading semiconductor players established roots in Austin decades ago and continue to expand their presence. Samsung is a great example, recently announcing that Austin will house its next US-based fab, adding to its existing 92,000 wafer per month capacity in the area. Like Silicon Valley, Austin boasts diverse semiconductor value chain activity, ranging from EDA to design, manufacturing, and equipment.

Exhibit 40: North America Semiconductor Ecosystem (Note: illustrative geographic value chain clustering; semiconductor companies across each stage of the value chain are found in more than one region; does not include all semiconductor companies in each region)



APAC

East Asia poses many advantages for domestic semiconductor companies: lower OpEx due to lower cost of living and utilities, business-friendly environments, and proximity to the largest consumer markets. Semiconductor companies in the region achieve remarkable scale and efficiency gains, due to cost savings and bargaining power over suppliers. Today, nearly 75% of global capacity is concentrated in East Asia Japan, South Korea, Taiwan, and mainland China. Moreover, 100% of current global capacity in advanced 7nm and 5nm nodes is in East Asia, thanks to TSMC and Samsung.

Taiwan

Taiwan is a chip manufacturing, test, and assembly powerhouse that receives strong incentive support from the Taiwanese government. Taiwan is one of only two regions in the whole world capable of manufacturing 5nm process node and below.

China (including Shanghai, Shenzhen, Tianjin, and other cities)

China has abundant natural resources, low operating costs, and government investment to grow its domestic semiconductor ecosystem. China is strongest in semiconductor manufacturing and assembly but has begun to invest into design and leading-node technology (12nm and below). China also has the benefit of proximity to end users and electronic companies that drive the bulk of global demand.

Japan

Japan is a leading exporter of automotive and consumer electronics. While Japan commanded 50% of global semiconductor market share in the 1970s, it now only accounts for 10% and is subject to further decline.

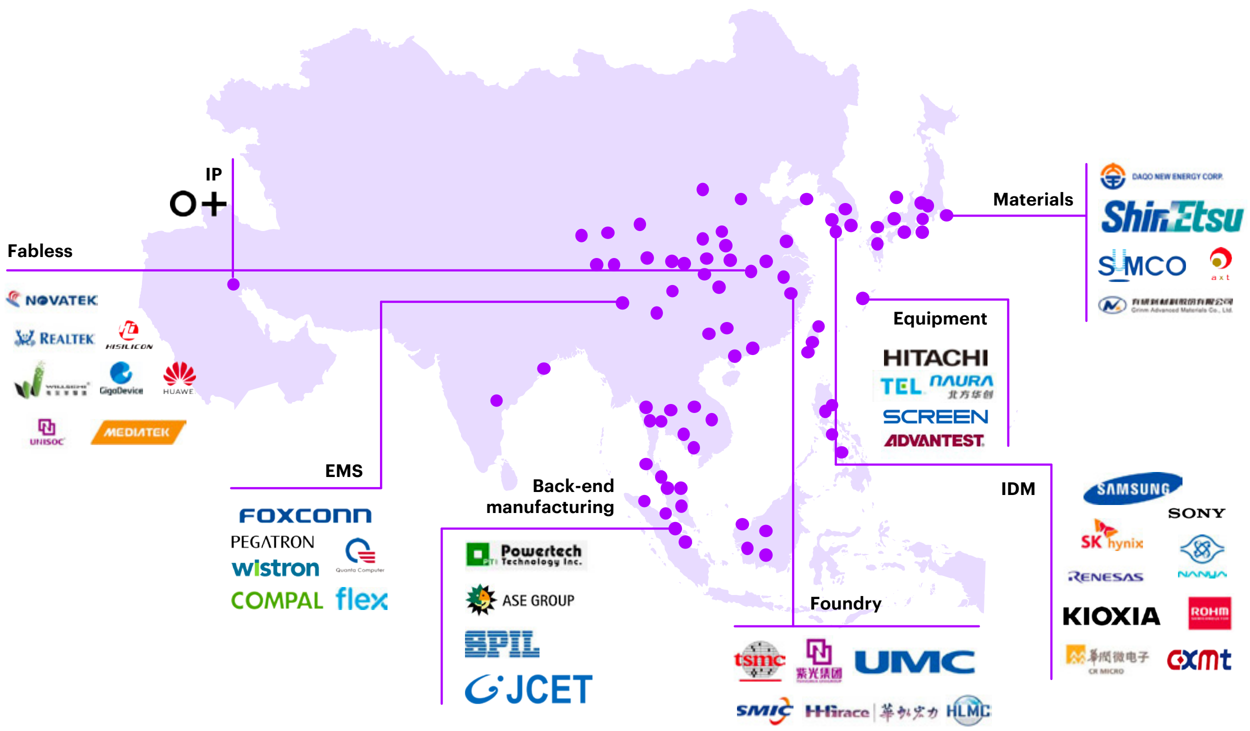
South Korea

South Korea is a leader in semiconductor exports, accounting for 18% of the global semiconductor market. South Korea is one of only two regions capable of advanced node manufacturing at 5nm node and below. South Korea's government is reinforcing its domestic semiconductor sector through subsidies and tax incentives over the coming decade.[100] South Korea's largest semiconductor companies, Samsung and SK Hynix, are also committing to large-scale investments. Samsung is expected to boost spending by 30% to 151B over the same time frame, whereas SK Hynix will invest $200B into new and existing facilities in Yongin.

Singapore

Singapore accounts for 5% of global wafer capacity, though Singapore's government recently announced its ambition to increase that to 50% by 2030.[122] Notably, GlobalFoundries announced a $4B expansion to expand chip capacity for automotive, 5G, and secure devices.[123] Singapore has deep industry-academia partnerships supported by world-class institutions including NUS, NTU, A*STAR (Agency for Science, Technology, and Research), which propel innovation for industry-wide R&D and chip design.

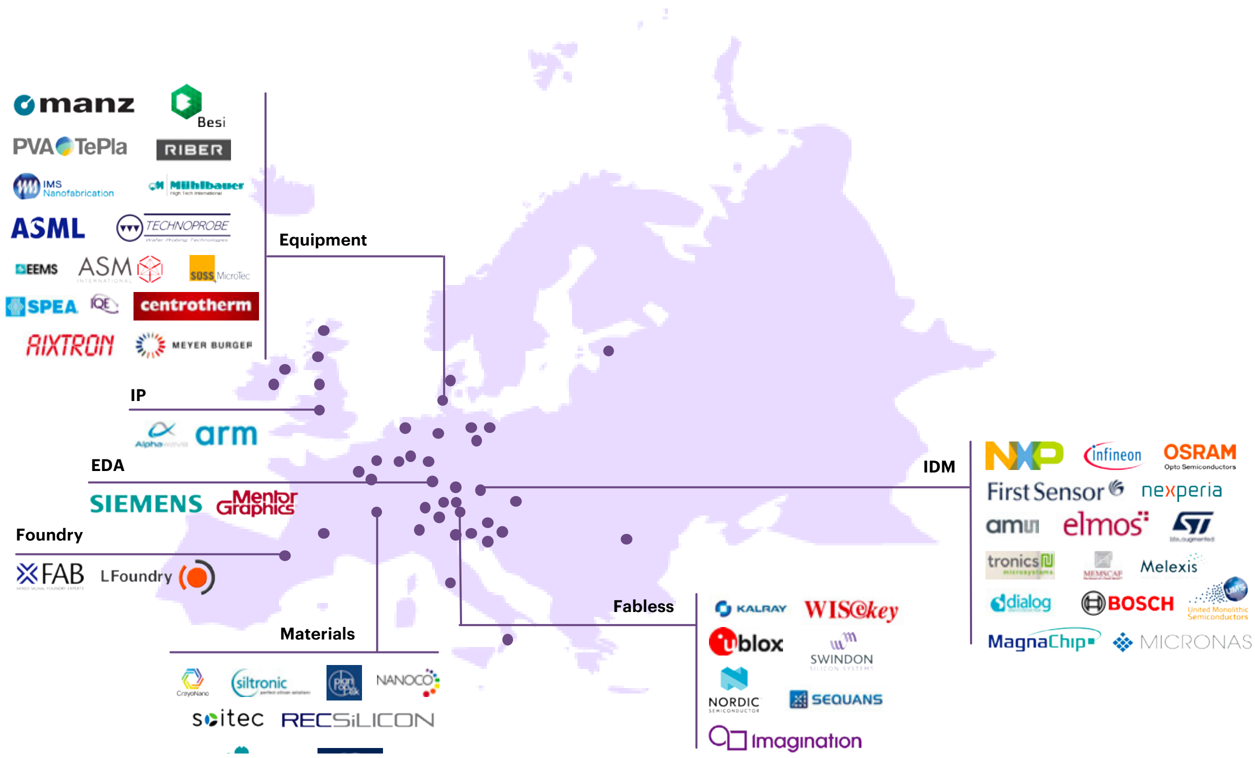
Exhibit 41: APAC Semiconductor Ecosystem (Note: illustrative geographic value chain clustering; semiconductor companies across each stage of the value chain are found in more than one region; does not include all semiconductor companies in each region)



Europe

Europe's chip sector specializes in semiconductor components for the region's leading industries: automotive and industrial. Chip production occurs near end users, leading to reduced shipment times, strengthened customer relationship, an intimate understanding of demand dynamics, and familiarity with local regulations.

Exhibit 42: European Semiconductor Ecosystem (Note: illustrative geographic value chain clustering; semiconductor companies across each stage of the value chain are found in more than one region; does not include all semiconductor companies in each region)

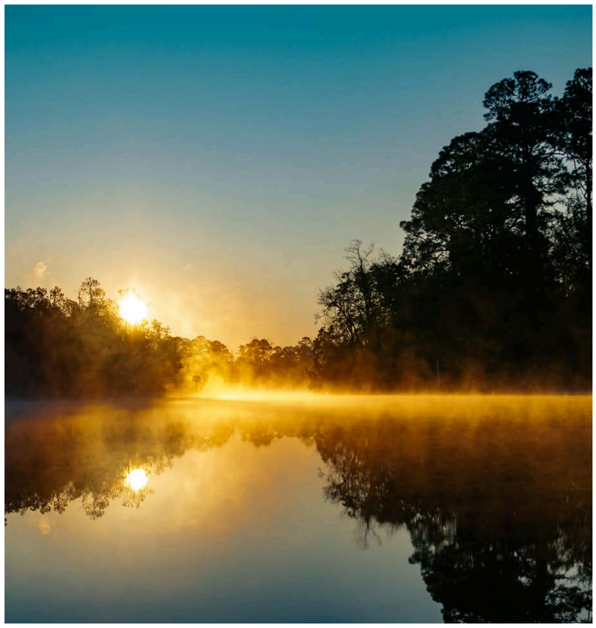


Regulation

Semiconductors weigh regulations and subsidies when deciding where to locate a new facility and how to structure their business, hire employees, and contract with suppliers. Whether environmental regulation, antitrust laws, IP laws, or regulation around foreign investment, regulations play a key role in semiconductor investment decisions.

Environmental regulation

Many countries have implemented hazardous waste regulations for semiconductor plants that in turn have directly influenced industry best practices. The EU's Waste Electrical and Equipment (WEEE) provides guidelines to minimize landfill wastage and its Restriction of Hazardous Substances (RoHS) restricts the use of lead and mercury in manufacturing various electronic materials, including those used in semiconductors. The US, China, Japan, and South Korea have all passed similar laws to regulate use of hazardous materials. California's Global Warming Solutions Act of 2006 includes regulations that specifically limit semiconductor companies' use of fluorinated gases or heat transfer fluids.



When building a new fab or expanding existing facilities, semiconductor companies must obtain land, zoning, and building permits from local authorities and tweak facility blueprints to local regulations. The speed at which permits can be obtained can influence semiconductor facility location assessments.

IP protection

Semiconductor companies are fiercely protective of their IP, their primary competitive advantage. Over the years, various IP protection regulations have been enacted. America's Semiconductor Chip Protection Act of 1984 bestows legal protection of chip topography and design layout IP. The EU's Legal Protection of Topographies of Semiconductor Products of 1986 protects IC design. In 1995, the World Trade Organization passed the Trade-Related Aspects of Intellectual Property (TRIPS) agreement, the first international trade agreement to define and mandate IP rules and enforcement procedures. The semiconductor industry has benefited from this sweeping framework as trade and IC design protections have encouraged firms to continue to innovate. To supplement IP regulations, semiconductor companies go to extraordinary lengths to protect their IP by maintaining black boxes only accessible to one person per fab, choosing highly secure operating locations, and keeping R&D teams separate from fab operations teams.

Government Incentives

Federal and local governments institute subsidies, tax holidays, and exemptions to attract investment from semiconductor companies. In 2013, GlobalFoundries chose to construct its new $4.2B semiconductor manufacturing facility in upstate New York. This deal, which included various grants and tax credits, was the largest private-public investment in the history of New York state. To attract domestic investment, Congress passed a law in 2020 that included a $750M multilateral security fund to support secure supply chain development and a 40% tax investment credit for semiconductor equipment and facilities.[124]

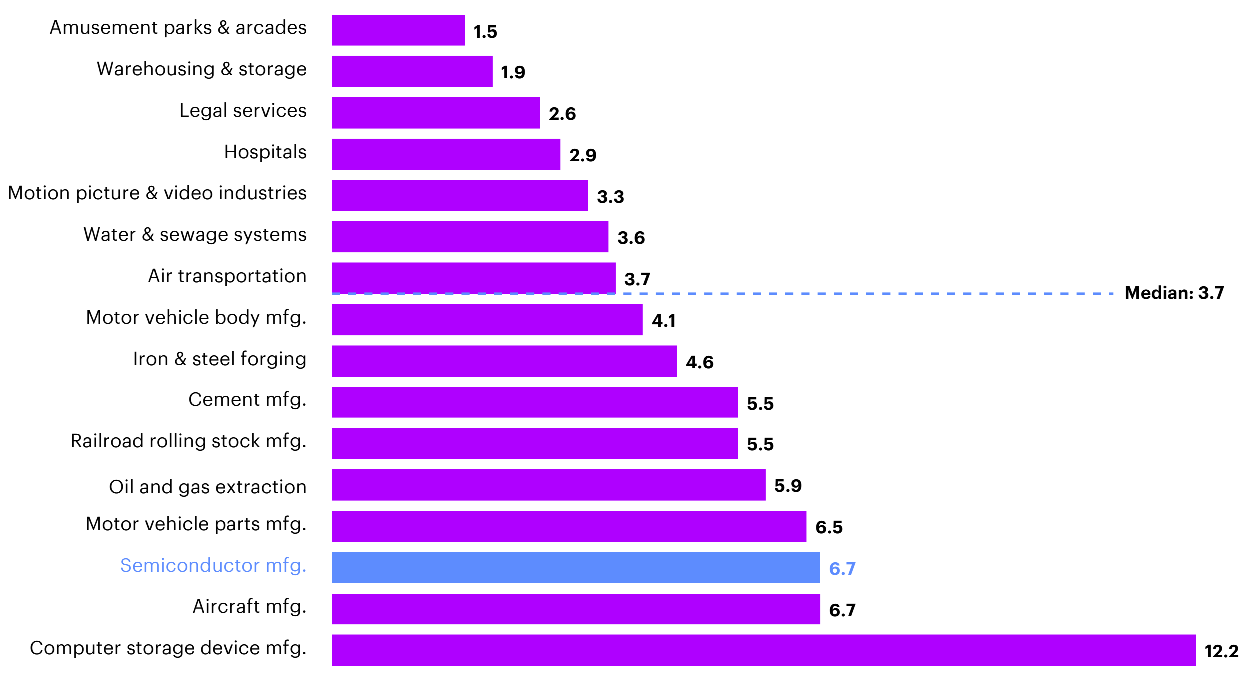
Likewise, in China, the government offers corporate income tax exemptions for key design and software firms, as well as preferential custom and tariff treatment for equipment makers.

Talent

Global semiconductor workforce

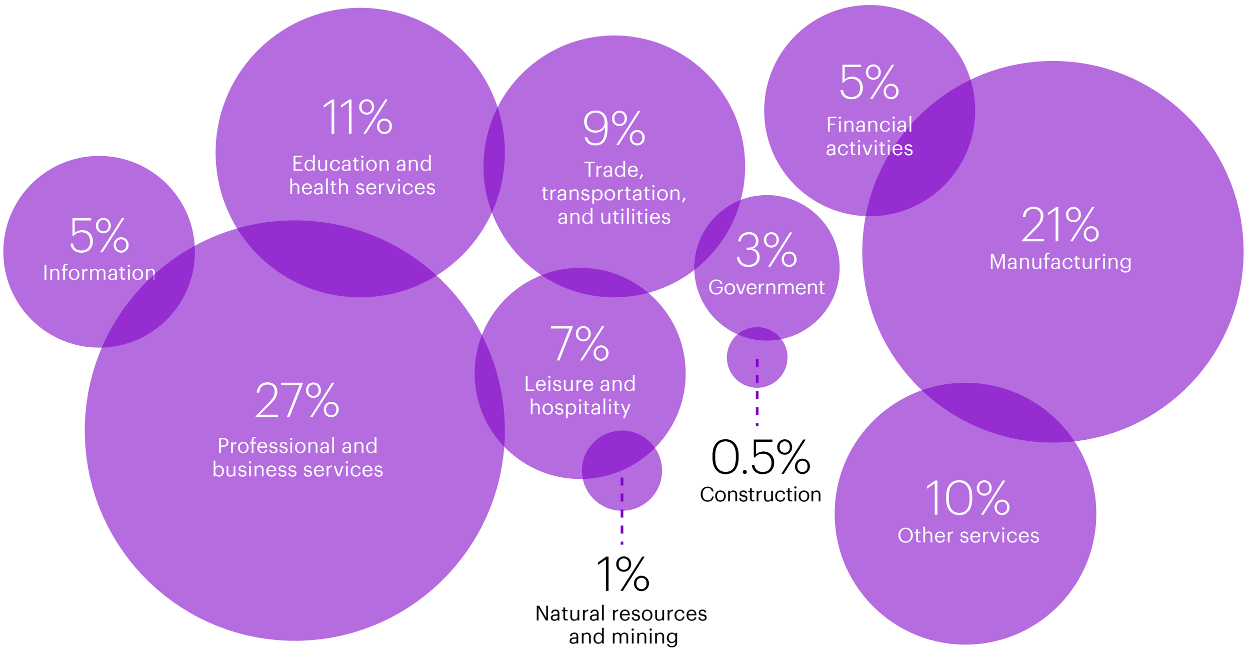
Human capital is the backbone of this industry. Engineers, data scientists, technicians and countless others are the ones who design, build, and deliver semiconductor chips that power our daily lives. Given the expansion in demand for semiconductor chips and new end products, it comes as no surprise that the semiconductor industry has a large labor footprint and an even larger footprint on downstream industries. The US semiconductor industry has a jobs multiplier of 6.7, meaning that for every direct job created in the domestic semiconductor industry, 5.7 additional jobs are supported in other downstream industries. Across 534 industries, semiconductor ranks at the 85th percentile in multiplicative job creation.

Exhibit 43: Employment multipliers in the US economy (source: IMPLAN Group)



The semiconductor industry requires skilled workers, with an extreme degree of technical specialization at any given stage of the value chain. For an industry that impacts roughly $250B of US GDP, it is only supported by an estimated 1.85M jobs.[125] Of the 1.85M jobs, 27% are in Professional and Business Services, 21% are in manufacturing and 11% are in Education and Health Services. Over 50% of workers in the semiconductor industry have at least a bachelor's degree and over a quarter have a graduate degree. Comparatively, in manufacturing, only 27% have at least a bachelor's degree.

Exhibit 44: Jobs impacted by semiconductor industry



In China, demand for labor and talent has also continued to grow and it has become a hot industry for applicants. In Q1 of 2021, recruiting demand for semiconductor jobs increased by over 65% compared to the same timeframe in 2020. Even though only 36% of jobs from semiconductor companies required at least a bachelor's degree, over 50% of applicants hired had at least a bachelor's degree.[126] For IC design, over 70% of workers had at least a bachelor's degree.[127] The country is turning its attention towards the front end of the value chain, and this is evident in the forecasted workforce demand. By 2022, 36% of workers will be in design, 35% in manufacturing, and 28% in packaging and testing.

However, China, like the US and the rest of the world, is facing a talent shortage. The industry itself is highly specialized and takes years of recruitment and investment to find the right candidates. In the face of planned and unplanned supply shocks, companies need to have mitigation strategies for their workforce to reduce downtime and bolster innovation. The breakneck speed of innovation and demand in this industry requires a strong pipeline of specialized talent who will build the products of today and unlock the possibilities of tomorrow.

5

Recommendations to boost industry resiliency

Over the years, the semiconductor industry has transformed into a globally intertwined web of firms with geographic specialization across the value chain. The US, once the global leader, has slowly been losing its edge in both semiconductor R&D and manufacturing. Europe, South Korea, Japan, Taiwan, and China are rapidly strengthening their own domestic semiconductor sectors, threatening America's leading position in the value chain. However, for an industry as expansive as semiconductors, it is neither possible nor advantageous for the US, or any country, to have complete autonomy over end-to-end semiconductor production. Thus, the industry will remain a deeply complex, interconnected web of global partners.

In this penultimate section of the report, we will apply a closer lens into historical and contemporary actions that have enabled each regional hub to dominate within their respective niches in the semiconductor ecosystem. We will then outline tangible levers that can have a meaningful impact on both domestic and global semiconductor ecosystems and fortify global value chain interconnectedness, upon which future innovation depends.

Protectionism doesn't support Moore's Law

Implemented to strengthen domestic economic activity and combat national security concerns, protectionism within the context of domestic capabilities has gained momentum in the semiconductor industry. As a recent example, the Trump Administration's export control policies prevented Huawei's HiSilicon chip design unit from contracting with an array of US-based chip manufacturers. The Trump Administration also restricted SMIC, China's largest chip manufacturer, from buying advanced manufacturing equipment from abroad—a powerful restriction, given the necessary technology and high switching costs associated with semiconductor manufacturing. Though intended to strengthen US semiconductor self-sufficiency, two unanticipated consequences resulted: disruption in global 5G rollout and Beijing doubling down on domestic chip production, which is likely to increase China's share of semiconductor manufacturing over the coming decade.

While stimulating domestic manufacturing is a noble goal, it may ultimately stifle cross-border flow of IP, design, components, and equipment that are integral to propelling the industry forward. In failing to account for the necessary geographical dependencies across the value chain, protectionism risks drastically undercutting the collaboration that is necessary to advance innovation. As an example, the rise and fall of the Japanese semiconductor industry in the 1980s illustrated how overinvestment in only one technology can result in getting blindsided by emerging technologies and inability to adopt innovative business models. In the 1980s, Japan quickly became the world's dominant manufacturer of DRAM memory. Japanese manufacturers produced these chips at a higher quality and lower cost than the US players, leading to a major customer shift towards purchasing Japanese products. However, the Japanese semiconductor market quickly found itself over-saturated in DRAM production, with minimal agility to pivot to design and production of next generation chips. In the same time frame, Japan missed out on the industry's pivot towards the fabless-foundry business model. As a result of these events, Japan was eventually supplanted by South Korea in memory and the US and Taiwan in logic.

Promoting innovation over isolationism

America's ascent in the semiconductor industry is a direct result of investment in innovation, not isolationism. In the 1980s, US chip companies pushed the Reagan Administration to enact tariffs on Japanese imports and guarantee additional semiconductor subsidies. However, these actions achieved little in rebuilding the US semiconductor industry, as only one American memory chip company—Micron—remained competitive in DRAM.

Core to America's renewed success in semiconductor was Intel's strategic focus on high-value chips and the rise of EDA tools.

- Rather than try to compete with Japanese players in DRAM, Intel pivoted to producing chips for PCs. Intel locked in one of the first contracts with IBM and hired the nation's top hardware engineers. This built a foundation for a period of profitability from the 1990s-2000s as Microsoft and IBM gained momentum and PCs became a mainstream staple of life, business, and academia.
- The US also achieved a head start in EDA innovation because it made an early investment in innovation centers and academic programs focused squarely on EDA development. In 1982, researchers at the Semiconductor Research Consortium identified the high-growth potential of EDA chip design software and pushed for the US government to establish centers of excellence at Carnegie Mellon University and the University of California, Berkeley. Investment in academia resulted in an influx of semiconductor software companies that eventually merged into three firms that dominate the EDA space today: Cadence, Synopsys, and Mentor Graphics.

As shown above, two prerequisites are required to remain competitive in the semiconductor industry: deep understanding of how the technology landscape will be disrupted by cutting-edge trends and strong ecosystem collaboration to bring innovation to life. Considering the ballooning costs of chip production, increased collaboration across the end-to-end value chain will prove paramount in maximizing return on investment to push the industry forward. **Those who forge strategic partnerships to develop joint technology roadmaps will have the long-term competitive advantage.** Recent industry history has been defined by semiconductor companies who have placed big bets by way of M&A deals. Future industry history will also be won by those who place big bets in the form of new partnership models, pooling R&D investment into similar areas that expedite industry progress.

Protecting semiconductor IP

Underpinning as innovation-intensive of an industry as semiconductor is IP, either in the form of core design IP blocks or core manufacturing processes. IP is a semiconductor company's secret sauce, particularly in enabling IP-centric EDA houses, fabless firms, and equipment manufacturers to maintain competitive advantage. The industry is defined by IP push-and-pull, balancing an increased need for cross-border ecosystem collaboration with protection of differentiated trade secrets. The introduction of global landmark WTO agreements such as TRIPS to protect IP has drastically increased the flow of goods across borders and spurred innovation, but they have also heightened the risk of IP theft.

Semiconductor IP theft is more complicated to execute than it may seem, given the technical know-how to reverse-engineer the minutiae of a company's complex semiconductor capabilities. Nonetheless, a growing number of semiconductor companies have engaged in high-profile patent litigation cases, underscoring how important semiconductor IP theft is to address. Semiconductor design protection, cybersecurity, and anti-counterfeiting measures that prevent counterfeit chips from polluting the supply chain will be critical in ensuring continued collaboration within the industry.[128]

Infusing the ecosystem with government subsidies

To spur onshore semiconductor activity, governments around the world provide subsidies in the form of tax incentives, discounted land cost, infrastructure and facility support, and low-cost financing.[129] **Core to the calculus of a government subsidy, however, is that it considers the whole semiconductor value chain rather than fix just one broken link**. Emphasizing one part of the value chain will only further strain the semiconductor ecosystem. As explained in prior sections, the semiconductor industry is defined by long lead times in R&D, design, and manufacturing, thereby requiring a long-term view around subsidy planning (e.g., minimum of 10-year time frame.

The semiconductor industry is the most R&D-intensive industry in the world, with semiconductor companies reinvesting a large share of their profits into technology development. This is especially true for fabless companies, who invest more than 20% of sales into R&D, or risk obsoletion in a quickly crowding space with mounting threat from well-funded startups and hyperscalers. **Government subsidies can strengthen companies' ability to compete against global competitors, but subsidies are not meant to serve as a one-time patch fix**. Continuous, long-term engagement with municipal and national governments is a surefire way for semiconductor companies to survive in a hyper-competitive, rapidly evolving landscape.

It is important, however, to note that even long-term subsidies alone will not automatically result in semiconductor success. One real world case study is the history of China and its attempt to achieve semiconductor self-sufficiency, which started 20 years ago.[130] Despite north of $300B being poured into multiple semiconductor projects, the nation still has not developed cutting edge chip design and manufacturing capability today. SMIC is mostly producing chips using 28nm node, though it has announced that it has mastered 14nm node. But even the latter means that they are still at least 3 generations and years behind TSMC or Samsung. A large amount of government subsidy results in waste, stillborn projects, and even unnatural market/pricing distortions. This case study provides hint that subsidies and monetary supports alone are not the solution to successfully make substantial progress in the semiconductor industry. Other levers such as workforce, which areas of the industry the subsidies go to, and rules and regulations play fundamental roles in building the foundation for a thriving local semiconductor industry.

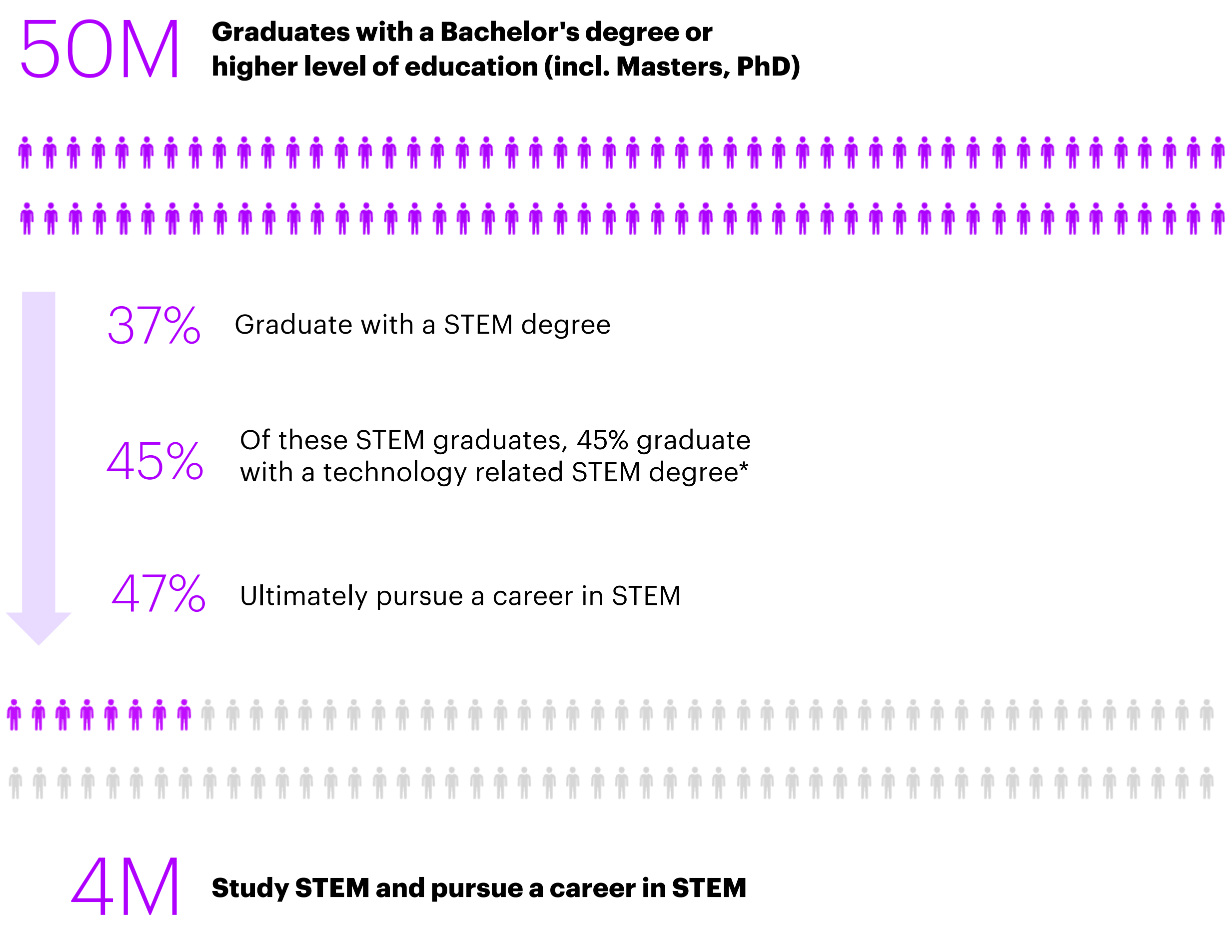
Exhibit 45: Foundry Capacity and International Semiconductor Subsidies.
Note: *Foundry capacity includes Malaysia, **Foundry capacity represents North America, ***Foundry capacity includes Middle East and Africa.

	200mm Foundry Capacity (2020)	300mm Foundry Capacity (2020)	Government Mfg. Incentives (2000-2020)	Government Mfg. Subsidies (2000-2020)	Proposed Government Legislation (2020-2030)	Government Mfg. Subsidies (2020-2030)
China	19%	15%	• Free/discounted land • Infra. support • Equipment leasing • Preferential loans	$50B	• Localization policies • Lower income tax rates	~$200B
South Korea	17%	7%	• Infra. support • Equipment incentives • Workforce training	$7-10B+	• Tax benefits and credits • K-semiconductor belt • Low-rate loans	n/a
Singapore*	6%	4%	• Equipment incentives • Hiring credits	$5B+	• n/a	n/a
Japan	1%	1%	• Preferential loans	$5-7B+	• Manufacturing technologies incentives • Decarbonization subsidies	~$43B
Taiwan	45%	64%	• Free/discounted land • Infra. support • Preferential loans • Workforce training	$0.5B	• Foundry expansion subsidies • R&D subsidies	~$27B
Europe	8%***	3%***	• Preferential loans	$2.5B	European Chips Act: • Semi research (IMEC, LETI, Fraunhofer) • Increase in domestic foundry capacity • Framework for international cooperation	~$167B
Israel	n/a	n/a	• Free/discounted land • Infra. support • Equipment incentives	$2.5B	• n/a	n/a
US**	4%	6%	• n/a	$0B	Chips Act: • Semi research and development • Development of foundries	~$52B

Addressing the talent shortage

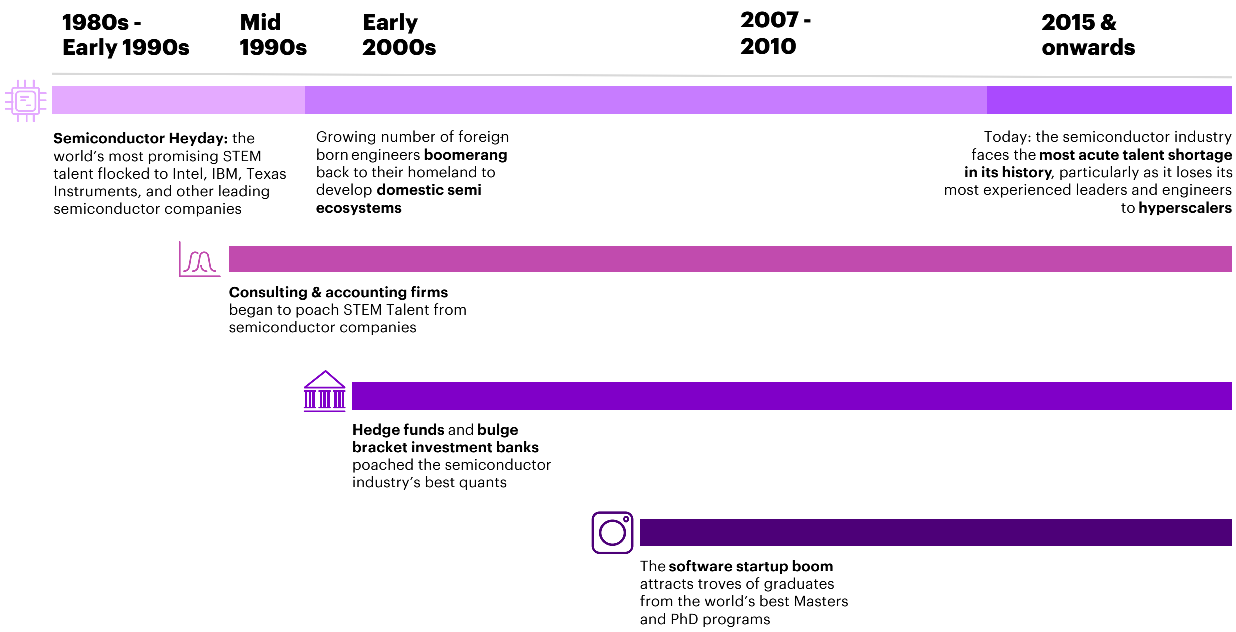
In the US, there are approximately 50M graduates with at least a Bachelor's degree or higher, with slightly more than 1/3 of this population graduating with STEM degrees. Among STEM graduates, those who pursue a career in STEM only amount to 4M.[131] Nearly 50% of Computer Science, Mathematics, and Statistics majors build careers outside of STEM, in fields ranging from finance to education. The US semiconductor industry is dependent on this pool of graduates to become the inventors and innovators of tomorrow, but the industry faces increasingly fierce competition to attract and maintain STEM talent.

Exhibit 46: US STEM graduates (source: US Census Bureau[131])
Note: Technology-related STEM degree excludes biological sciences, environmental sciences, agricultural sciences, psychology, social sciences, and multidisciplinary studies.



A high percentage of the semiconductor workforce has PhDs and Masters degrees. The industry enjoyed a great supply of highly skilled talents from its inception through the late 1990s. In the subsequent next two decades, the advent of internet and software giants created a new center of gravity where the promise of high wages and fast career growth lured traditional semiconductor talent. Subsequently, the semiconductor industry had to compete with these new players when it came to talents. As the software industry has been taking in a larger percentage of US college graduates and global talents every year, the semiconductor program size and research activities in the feeding universities and research institutions have been dwindling. This then leads to a smaller pool of semiconductor talents, which eventually perpetuates the cycle. We present here some potential areas that are important to assess when it comes to creating a sustainable and healthy talent pipeline for the semiconductor industry.

Exhibit 47: Exodus of semiconductor talent to tangential tech industries



Complicating the domestic semiconductor talent shortage are new global policies to lure STEM talent into their respective semiconductor ecosystems. For example, the "Thousand Talents Plan" within the Made in China 2025 initiative outlines a 1-5-3 recruiting strategy, wherein the Chinese government will offer South Korean semiconductor industry veterans and new college graduates five times the salary for a three-year commitment to work in China.[132] In addition to this, China has attracted more than 3,000 Taiwanese chip engineers by offering 2-3x the salary.[133]

Ecosystem participants (e.g., industry and academia and government entities can work together in enhancing the current education system and provide more avenues for the incubation and dissemination of semiconductor knowledge. This includes increased investment in curriculum updates geared towards semiconductor expertise development, research funding for next generation semiconductor technologies, scholarships with industrial attachment at leading semiconductor institutions, and internship opportunities in the semiconductor industry. New studies and surveys in collaboration with universities, research institutions, and industry partners can generate new insights on talent gaps and investment opportunities.

In Taiwan, TSMC has established four research centers in partnership with Taiwan's most prestigious university to introduce cutting edge semiconductor projects to students and to allow TSMC to cultivate a talent pipeline for the company. The company's partnership extends globally to universities such as Stanford and MIT to conduct research in areas such as process technology and wire technology. Professors, with their students, regularly engage with managers in the company to develop new design technologies.[134]

Looking earlier in the education system, another opportunity is to introduce or expand semiconductor foundation at the high school or secondary school level. As semiconductors become more pervasive in daily lives, it is important that young students understand the field, just like they do math and biology, and that they can explore it further. **By preparing students from young ages and equipping them with basic semiconductor engineering skillsets, the industry and the wider technology landscape can reap the benefit decades down the road**.

Learning from the explosion of the software industry in the last two decades, one of the key takeaways is the relatively lower barrier to entry with fast career growth in the field compared to the semiconductor industry. **While in the software world, one can self-teach, build, test, and sell a code him/herself, the same cannot be said about the current state of the semiconductor industry**. R&D and design require extensive engineering training while manufacturing requires highly skilled technicians. All are also quite expensive in the semiconductor realm, which discourages people from venturing into the industry. The question then is: how do we lower the cost to learn, build, and test a semiconductor chip? One opportunity is to enable low-cost experimental design and manufacturing centers through collaboration or joint ownership with ecosystem partners (e.g., EDA, IP, design, manufacturing, equipment maker, etc. where all parties acquire equity when new ideas successfully take off. With lower barrier to entry, more younger talents may find it easier to start learning, get involved, hone their skills, and eventually contribute to the field. And as the field becomes one where students can experiment with and apply their creativity, the momentum can build up and create a larger pool of talents in the long run.

Immigration systems have facilitated the development of semiconductor talent. In the US, for example, research conducted by the Center for Security and Emerging Technology showed that the number of American students in semiconductor-related graduate programs stayed relatively unchanged at 90,000 since the 1990s, while in the same period, the number of international students has increased from 50,000 to 140,000.[135]

Access to talent is critical for continued expansion and growth of the semiconductor industry and indeed the multitude of industries that depend on chips.

Investing in semiconductor R&D

While it is tempting to focus on addressing stopgaps in the chip shortage, maintaining leadership in the semiconductor industry requires a longer-term view of investment. TSMC recently announced that it would build a 5nm fab in Arizona, beginning production in 2024. However, by then, leading-edge technology will be at 3nm or below. For the US to maintain its semiconductor leadership, R&D efforts underway today need to be focused on the leading-edge, where chip production will only take place several years in the future. Nascent technologies that are not yet used in real-world applications, including quantum computing, 6G/7G/8G, and photonics-based AI chips, hold massive potential to revolutionize the future technological landscape. By focusing primarily on supercharging domestic manufacturing capacity for today's technological needs, the US will be unable to power these cutting-edge technologies in the future.

Historically, the US has been a pioneer in semiconductor R&D. However, South Korea, Taiwan, Japan, China, and the EU have ramped up R&D investments, recognizing both the importance of semiconductors to their economies and the increased competition in the global semiconductor landscape. In September of 2021, President Biden announced 30 business and research titans as members of the President's Council of Advisors on Science and Technology (PCAST. President Biden's PCAST, charged with offering STEM and innovation policy recommendations, includes semiconductor trailblazers Lisa Su (CEO of AMD) and Bill Dally (Chief Scientist of Nvidia).[136] Continued interlock among government bodies such as PCAST, semiconductor companies, research institutions, industry consortia, and academia will be crucial for the US to remain at the forefront of the ever-evolving semiconductor landscape. This interlock can take shape in several different ways, as shown in Exhibit 48 below.

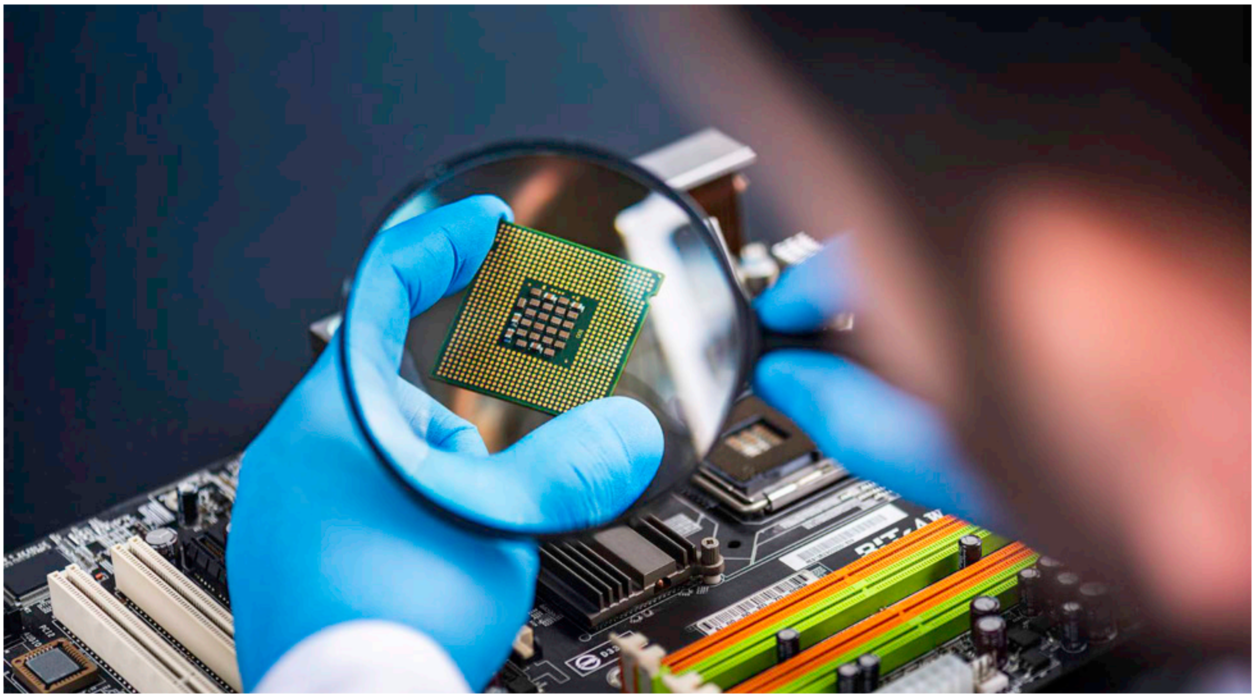
Exhibit 48: Semiconductor ecosystem collaboration models

Collaboration model	Description	Complicating factors	Example in industry
Research contract	Semiconductor company forges contract with academic institution to complete defined statement of work	Mismatch between rapid industry timeline and prolonged academic research timeline Corporate – university ownership of IP	In 2015, Texas Instruments awarded the Cockrell School of Engineering at The University of Texas at Austin $3.5M to launch TI Labs to advance electrical and computer engineering research efforts
Industrial grant	Semiconductor company makes a grant through an industrial research lab, which supports students' academic focus area	Lack of formal work product output/ deliverable	Since Qualcomm's Innovation Fellowship launched in 2009, Qualcomm has awarded more than $5M in grants to innovative university PhD students across a diverse array of technical research areas
Direct skill transfer	University supplies personnel to semiconductor company, rather than discrete work product. This enables both the semiconductor company and university to bypass contracting complexities, minimize tension around IP ownership, and facilitate stronger team integration	Risk that short-term personnel interaction can tarnish university training and research capabilities	University of Albany is a long-standing partner of GlobalFoundries. As of July 2021, GlobalFoundries launched a new partnership with UAlbany to strengthen the talent pipeline into its Fab 8 campus, located less than 30 miles away from UAlbany's campus.
Shared entity	Semiconductor company coinvests in a research lab that can take shape through on-site labs with both industry and academia, industry personnel staffed in university labs	Joint IP and/or pre-negotiated license structure needed for long-term agreement Flexible university practices needed to accommodate faculty, students, and staff in research lab (e.g., part-time leave of absence)	Research institute Leti and semiconductor leader STMicroelectronics have a deep-rooted R&D relationship. Cooperation between Leti and STMicroelectronics has resulted in a surge in imaging applications for smartphones. From dense 3D interconnect to autonomous imagers and GaN-on-silicon technology for power conversion applications, Leti has helped power some of STMicroelectronics' most prevalent breakthroughs in the industry
Community / consortium model	Industry consortium (e.g., SIA) shares research with community of semiconductor industry subscribers, thereby open-sourcing and democratizing research	Greater degree of interlock needed among semiconductor industry partners	Samsung, Intel, and TSMC co-invested in ASML's EUV lithography technology to accelerate development and adoption of a key piece of equipment to sustain innovation. Intel invested and owned 15% of ASML, TSMC 5%, and Samsung 3%.

Ensuring ecosystem-friendly business conditions

Overriding geopolitical concerns have implications for markets and supply. Stable business conditions support continuous innovation through R&D, which come straight from the revenue streams. With this stability, ecosystem players can collaborate by leveraging free flow of ideas, IPs, hardware, and other forms of assets that are required to innovate. In an industry such as semiconductors where big investments are made and success is defined in 5-10 years of time frame, predictable business conditions are key. Restricting access to markets and supply can have unintended consequences that are disadvantageous to all ecosystem players. When a technology or product by a company is used by fewer users, besides lower revenue and lower R&D funding, the company also risks becoming irrelevant in the market. Thus, export controls should be carefully considered so that restrictions on access to markets and supply do not unnecessarily damage this complex ecosystem in a way that sharply reduces revenues available for R&D investment.

Government policy can create uncertainty, and the whole industry is watching what the US government will do with its Entity List, and other export controls restricting semiconductor sector trade. A turbulent political climate can be detrimental to the free flow of ideas, IP, hardware, and other forms of assets that are required for collaboration and innovation. Tight export control results in lower activity of technology cross-pollination between countries. Restriction on access to certain semi tools (e.g., EDA, IP, equipment), access to foundry and assembly capacity, or access to raw materials can hurt the impacted entity in the short term but encourage their domestic development and self-sufficiency in the long run. Export controls could have an impact on national security (e.g., by harming the supply of chips needed for applications in cybersecurity, defense, and military vehicles) and on the domestic economy (e.g., through the dependence of other industries on semiconductor).



6

Conclusion

The boom-and-bust cycles in the semiconductor industry occurred even before the COVID-19 pandemic. However, what differentiates this cycle is the degree of impact and extent to which daily activities are affected due to the proliferation of smart devices. The natural progression towards specialization in the semiconductor industry is the result of ever-increasing technical complexity and rising costs. To sustain advancements in semiconductor technology, it is important to implement key ingredients for success to ensure that complexity is no longer a deterrent for future innovation.

The COVID-19 induced chip shortage highlighted the weakest links of the semiconductor industry. While government incentives are crucial to address these links in the near-term, equally if not more important are activities to strengthen resiliency of the broader global value chain in the long-term. As one of the most capital and planning-intensive industries, long-term industry success relies on a stable business environment that enables collaboration among all ecosystem players. Furthermore, a strong STEM talent pipeline is key to sustaining the flow of a highly skilled workforce into the industry that powers broad technological innovation. Continuous alignment between ecosystem players and policymakers is crucial to address supply chain challenges from a holistic lens, fortify the global value chain, and continue the fast pace of innovation that is native to the semiconductor industry.

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