The Growing Challenge of Semiconductor Design Leadership

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Executive Summary

Semiconductors are ubiquitous, powering technologies that range from cell phones to the Mars rovers Curiosity and Perseverance, and economically important. In 2021, worldwide semiconductor sales totaled $556 billion. Semiconductor design—which includes design of both physical integrated circuits and associated software—accounts for roughly half of all industry R&D investment and value add.[1]

US companies have played a leading role in semiconductor design, and as a result the US has benefited from a virtuous cycle of innovation, enhancing its ability to shape technical standards, strengthen national security, offer high-quality employment, and generate competitive advantage for original equipment manufacturers (OEMs) in adjacent industries. (See Exhibit 1.)

In recent years, however, the US's share of design-related revenues has begun to show signs of a decline, dropping from over 50% in 2015 to 46% in 2020.[2] Other regions, especially South Korea and China, are seeing local growth in their design capabilities. Our analysis shows that at the current trajectory (that is, if planners take no action), the US share could fall to 36% by the end of this decade as other regions capture a larger share of future growth.

Should the US aim to defend its leadership position in design and reap the associated downstream benefits of design leadership, it would need to address three challenges.

Challenge 1: Design and R&D investment needs are rising. As chips have grown more complex, development costs have risen, especially for chips made on leading-edge manufacturing nodes. Today, the US private sector invests more in design R&D than any other region's private sector does, but governments around the world offer significant incentives to attract advanced design, and the US risks falling behind. In addition, the relative level of public support for R&D in the US lags that of other regions. The overall share of semiconductor-specific design and R&D funded by public investment is 13% in the US, compared to an average of 30% across mainland China, Europe, Taiwan, Japan, and South Korea. Bringing US public investment in design and R&D into line with international peers—including, for example, direct incentives such as tax credits for advanced design and R&D performed in the US—will help ensure a level playing field for design in the US relative to other regions.

Challenge 2: The supply of design talent is dwindling. Although most of the world's semiconductor design engineers today are based in the US, the US semiconductor design industry faces a shortage of skilled workers and is on track to see this shortage increase to 23,000 designers by 2030, given trends in the number of science, technology, engineering, and mathematics (STEM) graduates and the number of experienced engineers leaving the industry. Public and private sectors must work together to encourage more US workers to enter the field of design, as well as to encourage experienced designers not to leave the field or the country. Further, the private sector must continue to enhance the productivity of its workforce by developing and deploying new tools and prioritizing the highest value-add R&D and design.

Challenge 3: Open access to global markets is under pressure. Sales are the ultimate source of funding for investment in R&D, but tariffs, export restrictions, and other factors threaten US semiconductor players' access to global markets, implicitly putting R&D reinvestment at risk. Secular trends may reverse some elements of globalization, but ensuring that markets remain as open as possible will benefit the US, which gains significantly from free trade and has the most to lose from proliferating restrictions.

1. Industry value add is the amount by which the value of an article increases at each stage of its production, exclusive of initial costs.
2. Design revenue calculations are based on fabless companies and estimated share of integrated device manufacturer (IDM) revenues attributable to design.

The US private sector is likely to invest $400 billion to $500 billion over the next ten years in design-related activities, including R&D and workforce development. But to maintain leadership over the coming decade, the US needs complementary public-sector investments aimed at addressing the key challenges laid out above to strengthen both the domestic semiconductor industry and the country as a whole.

Further, the leverage provided by public-sector investments would be substantial. Our analysis suggests that each public dollar invested in design and R&D would induce additional private-sector investment in design and R&D, ultimately yielding $18 to $24 of design-related sales.[3]

As a result, public investment in design and R&D of approximately $20 billion to $30 billion through 2030 (including a $15 billion to $20 billion design tax incentive) would yield incremental design-related sales of about $450 billion over ten years, while also supporting training and employment for about 23,000 design jobs and 130,000 indirect and induced jobs, and fortifying the US leadership position in semiconductor design.

Exhibit 1 - Market Leadership in Semiconductor Design Confers Multiple Advantages

Virtuous cycle of innovation

Leadership attracts global talent and contributes to a cycle of innovation and reinvestment

Ability to shape standards

First movers have an advantage in setting and leveraging the benefits of global technical standards

Stronger security

National security benefits from improved defense systems at lower risk of tampering and disruption

High-quality employment

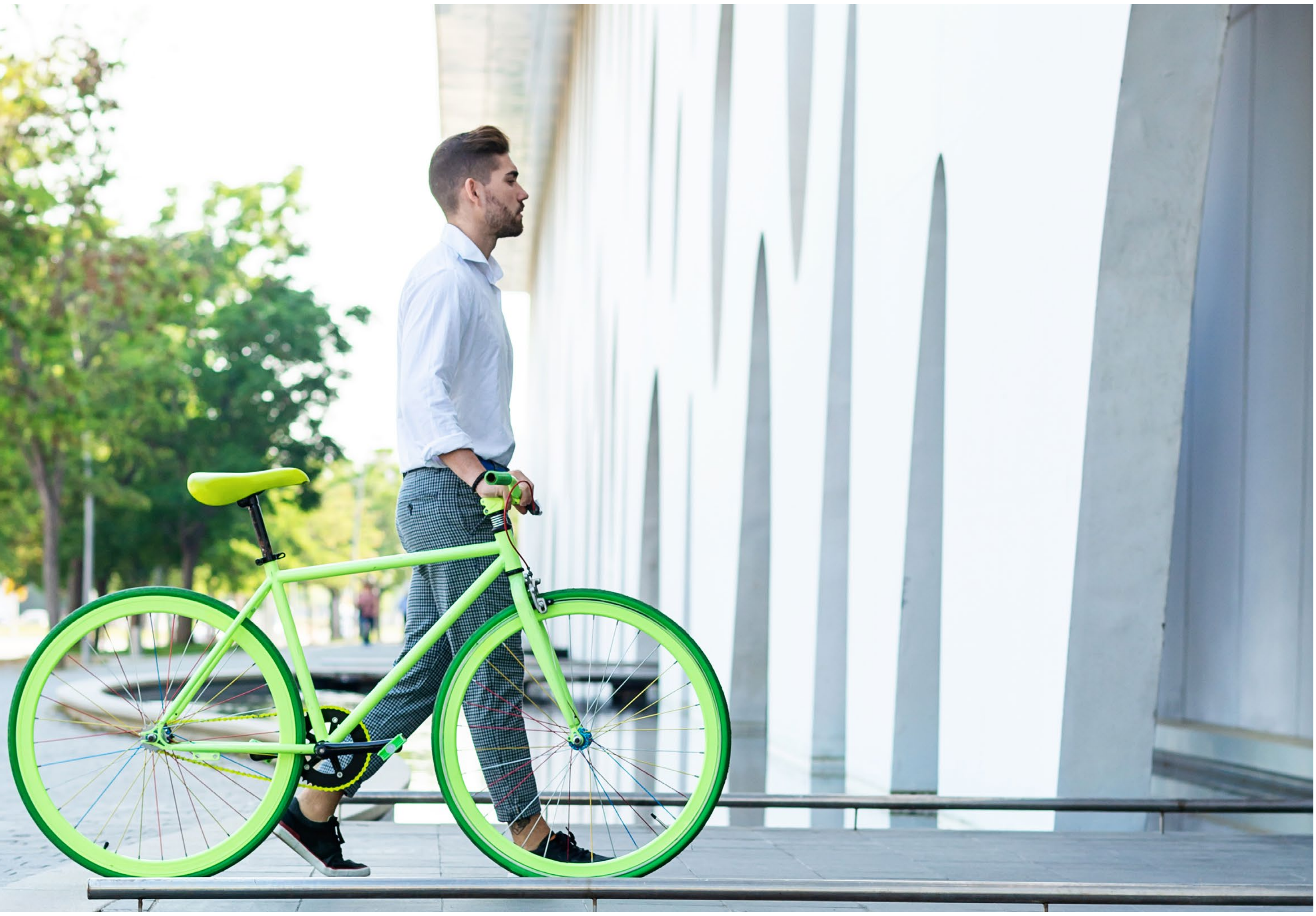
The average annual income of workers employed in semiconductor design was $170,000, compared to the US median of $56,000

Benefits for OEMs

Close collaboration between OEMs and local design teams creates competitive advantage

Source: BCG analysis.

3. These calculations assume that each public dollar invested in design and R&D induces an additional $2 to $3 of private-sector R&D investment and that each incremental dollar of R&D yields $6 of incremental sales.



The Growing Challenge of Semiconductor Design Leadership

Semiconductors are critical to the functioning of the modern world driving economic competitiveness, national security, and technologies ranging from modern defense capabilities to autonomous vehicles. The semiconductor industry is of high strategic importance and semiconductor manufacturing is increasingly the focus of industrial policies across major economies.

Before semiconductors or chips can be manufactured, however, they must be designed, and this report focuses on the design of semiconductors.

We start by laying out what semiconductor design is and why it is important, and we discuss the US's history in this domain as well as the benefits that design leadership has conferred. Despite its high value, leadership in design is not inevitable, and today the US faces three key challenges to maintaining its position as a market leader: increasing difficulty and R&D intensity associated with semiconductor design; a shortage of domestic talent; and threats to global market access that enable ongoing reinvestment in design.

We estimate the impact of the talent shortage on US design leadership and the possible benefits and returns of potential policies the US could pursue if it chose to sustain leadership in semiconductor design.

Design Is a Critical Part of the Semiconductor Value Chain

In building a house, architects and building engineers work together to design the high-level layout of, for example, a colonial or post-modern home. These professionals determine where to position rooms and windows to create a space that meets their client's needs. Architects and building engineers must consider a range of tradeoffs—for example, between living space and storage space—and lay out the detailed framing, plumbing, electrical, and other considerations that make a home livable. All of this preparatory work must occur before actual construction can begin.

Similarly, before semiconductors can be manufactured, they must be designed. And just as tradeoffs are necessary in home design—for example, between openness and privacy—chip design requires tradeoffs between such desirable objectives as performance and power efficiency, the processing of general instructions and the processing of highly specialized instructions, and inputs of digital data and inputs of real-world analog data.

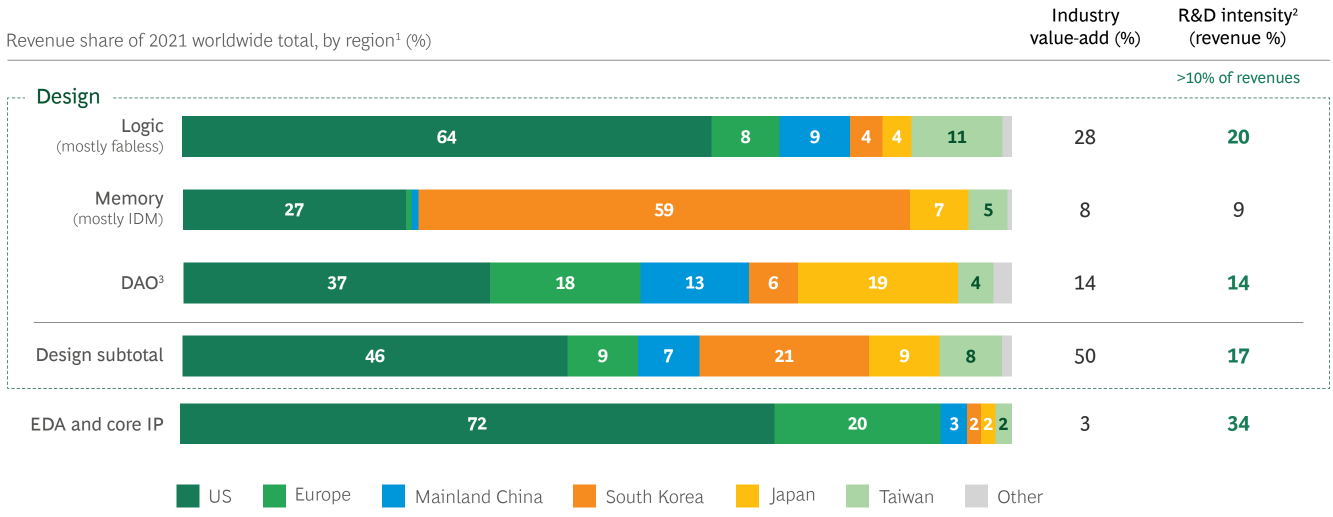
And just as expertise in designing single-family homes does not qualify an architect to design a skyscraper, the skills needed to design chips for different applications are in many cases not fungible. (See "Key Semiconductor Design Technologies," in the Appendix.) Further, chip design can be a massive undertaking that requires large teams—sometimes including hundreds of highly skilled design engineers, each with different specialties—to collaborate for years before a design is complete and ready for production. Historically, the US has led the world in semiconductor design. (See Exhibit 2.)

Well-designed chips enable automobiles to operate safely, advanced medical equipment to preserve or save lives, and military radar systems to detect dangers. Semiconductor design has helped make virtually all sectors of the economy, from farming to manufacturing, more effective and efficient. Semiconductor design has also been pivotal in new innovations, such as artificial intelligence (AI), that are transforming entire areas of technology and the economy.

When semiconductor design improves, all applications that use semiconductors benefit as well. Conversely, when semiconductor design stagnates, all related applications suffer too. In addition, design innovation is fundamental to future semiconductor improvements. As physical scaling difficulties continue to increase, design-related innovations such as new architectures and heterogeneous integration will be increasingly important. Heterogeneous integration will improve performance by allowing designers to choose among the best possible manufacturing technologies for different elements of each chip (for example, power management on silicon carbide, analog functions on 28nm, and high-performance logic on leading-edge node sizes) and deliver levels of overall performance that were previously impossible.

Design is the key activity that differentiates one semiconductor from another and guides how raw silicon wafers become state-of-the-art chips, so it's no surprise that design requires significant R&D investment. (See "Summary of the Semiconductor Value Chain" in the Appendix.) In fact, the R&D intensity of design is about 20%, and the R&D intensity of EDA and core IP is greater than 30%, compared to about 10% for wafer fabrication and equipment production.

Exhibit 2 - The US Is the Longstanding Leader in Semiconductor Design



Sources: Capital IQ; SIA Factbook 2022; BCG analysis.

Note: DAO = discrete, analog, and other; EDA = electronic design automation; IP = intellectual property. Because of rounding, not all bar segment totals add up to 100%.

¹The regional breakdown is based on company revenues and headquarters location. Design revenues are based on fabless companies and estimated share of IDM revenues attributable to design.

²R&D intensity is measured as R&D divided by revenue.

³Discrete, analog, optoelectronics, sensors, and others.

Design Is Complex and Includes Multiple Different Types of Firms and Activities

Semiconductor design involves two types of activities: hardware design and software development work. Hardware design is a multistep process encompassing product definition and specification, system design, integrated circuit design, and post-silicon validation. (See Exhibit 3.) Software development entails the creation of firmware—a type of lower-level software that bypasses (for example) the operating system of an end device, like a laptop, to provide instructions directly to a chip. As design grows more complex, it becomes an increasingly iterative process—especially for leading players—that occurs in parallel in order to surface issues earlier, optimize overall system-level performance, and decrease time to market.

Hardware designers use both new and established techniques in the design process. When driving innovations, designers generate new, specialized designs that enable specific applications to leverage the latest advances in design and related technologies. Designers will often use existing, reusable architectural building blocks (core IP) to simplify and accelerate creation of the overall design. In all cases, designers use highly advanced EDA software to automate the design process and ensure that chip designs can be manufactured on distinct and often proprietary fabrication processes. Since a single chip can house billions of transistors, state-of-the-art EDA tools are indispensable for designing modern semiconductors. (See "Types of Semiconductor Design Activities" in the Appendix.)

Many kinds of companies engage in semiconductor design, but they fall into four main categories:

- **Fabless Companies.** Responsible for roughly half of design-related value add, these companies focus on chip design. They partner with third-party merchant foundries to fabricate (that is, manufacture) their chips.

- **Integrated Device Manufacturers (IDMs).** Responsible for about half of design-related value add, IDMs both design and manufacture chips. Within IDMs, design and manufacturing teams work together to bring new chips to market, usually at in-house fabrication facilities.

- **Original Equipment Manufacturers (OEMs).** OEMs, such as auto makers, also play a role in semiconductor design. They use semiconductors as inputs for other products. Some OEMs have begun to design their own chips, chiefly for their own products. For example, a cloud computing provider may design custom chips with specific features that execute specific tasks very well.[4] OEMs are a growing presence in chip design and increasingly participate in the same product and talent markets that fabless companies and IDMs tap for their needs.

- **EDA/IP Providers.** EDA companies are trusted intermediaries between design companies and foundries, providing design tools, reference flows and some services. US leadership in EDA tools confers significant benefits to US semiconductor design, as researchers have greater access to automation tools, to the engineers behind those tools and to support for experimentation with new design concepts. Third-party IP providers design and license IP building blocks (processors, libraries, memories, interfaces, sensors, and security).

In addition to these players, design services companies—which can be third-party providers or in-house teams at manufacturers—perform a valuable function in developing and optimizing new designs. In particular, fabless companies often work closely with a given foundry's design services team to ensure the compatibility of its designs with the foundry's fabrication processes. (See the sidebar "Spotlight on the Fabless-Foundry Ecosystem.") Close collaboration is critical, as scaling up new processes involves inherent uncertainties in modeling and reaching target manufacturing yields.

Exhibit 3 - The Semiconductor Hardware Design Process Consists of Four Major Stages

1 Product definition and specification

Product management, system architecture, and customer define initial product requirements

2 Architecture/system design

System architects define block-level architecture for the design and may leverage previous IP

3 Integrated circuit design

Multidisciplinary effort:

- Logic: Initial analog and digital design
- Circuit: Digital synthesis and design for test
- Layout: Routing and mask generation

Verification

Verification engineers verify design functionality and timing through simulation

4 Post-silicon validation

Validation engineers validate physical device functionality across extreme working conditions

Sources: White House 100 Day Supply Chain Review Report; BCG analysis.

4. For example, Graviton, a family of chips designed by Amazon Web Services, includes features that allow chips to refresh their firmware to address issues without disturbing customers that are using the machine for other purposes.

Spotlight on the Fabless-Foundry Ecosystem

In the mid-1980s, large and vertically integrated IDMs (integrated device manufacturers) performed all semiconductor design and fabrication. Seeking to offset the high capital expenditure required for fabrication equipment, IDMs began to make unused manufacturing capacity available to smaller companies to keep their fabs busy. While this enabled some companies with design expertise to produce chips without operating their own fabs, it remained a small part of IDMs' businesses. IDMs often preferred to own the designs they fabricated, and they found it difficult to balance the needs of internal and external customers.

In 1987, Dr. Morris Chang sensed an opportunity and—in partnership with the Taiwanese government and Philips Semiconductor—launched Taiwan Semiconductor Manufacturing Company (TSMC), the world's first "pure-play" foundry (one involved exclusively in manufacturing and not in product design). TSMC assured its customers that as a dedicated foundry, it would not compete with them in design.

TSMC adopted a low-cost pricing strategy that depended on high-volume production for profitability. Although it sacrificed early profits, the company's market share for fabrication rapidly grew, allowing it to recoup its large capital expenditures and invest in next-generation technology nodes. TSMC was among the companies that benefited from the Taiwanese government's broad support for the semiconductor industry, through R&D assistance, workforce training, the establishment of high-tech corporate parks, and more.

Although both the IDM model and the foundry model have their advantages, the emergence of pure-play foundries lowered barriers to entry for design companies and revolutionized the industry, leading to the emergence of fabless semiconductor design firms. Free of the large capital expenditures of manufacturing, fabless companies could focus their expertise and resources on innovations in design and partner with dedicated foundries for fabrication.

Because the technology of semiconductor design evolves continually, design leaders must leverage new and future technologies that are critical for design innovation, including these:

- **Hardware and Software Co-design.** As systems become more complex, designers leverage practices such as design technology co-optimization (DTCO) and system technology co-optimization (STCO) to ensure that an improvement in one area does not create problems for overall system-level performance. "Shift-left" design principles permit parallel software and hardware development by leveraging virtual prototyping and digital twins.

- **AI-Based Design.** Designers can more quickly and effectively meet power, performance, and area targets by leveraging AI-based tools. Reinforcement learning and other AI algorithms can automate less consequential design tasks, freeing engineers to focus on more advanced tasks and decisions.

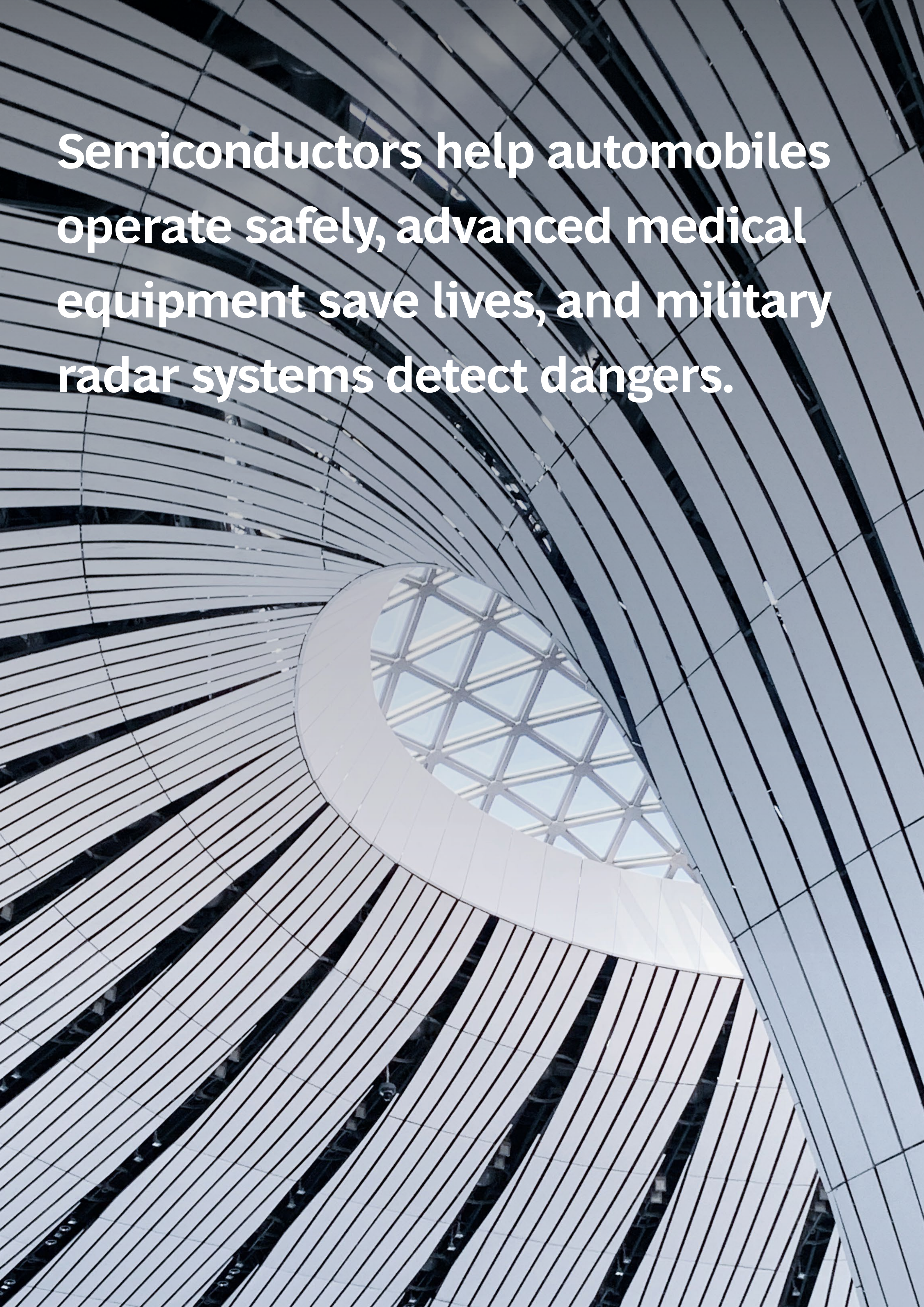
- **2.5D/3D Designs, Chiplets, and Heterogeneous Integration.** As the adoption of new process technologies slows, design engineers have been moving to new design, integration, and packaging technologies that help improve performance and reduce cost and power consumption. Heterogeneous integration permits increased use of highly specialized designs to further improve performance.

- **Secure Design.** Increased scrutiny on the security of semiconductor designs is prompting designers to place more emphasis on secure hardware modules and to develop enhanced tools, methods, and encryption. Designing security into semiconductors at the hardware level ensures that systems behave as expected, prevents faults, and enhances cybersecurity.

To Date, the US has Enjoyed the Benefits of Leading the World in Semiconductor Design

As of 2021, 46% of semiconductor industry revenues were attributable to the design activities of US-headquartered companies, nearly 2.5 times as much as any other individual region. US market leadership in design is most pronounced in logic, generating 64% of design-related revenues in that sector, but it also extends to the design of discrete, analog, and other (DAO) devices, where US-headquartered companies generate 37% of design-related revenues. Only in memory, where South Korean firms generate 59% of all design-related revenues, does the US not have a market leading position, as detailed in Exhibit 2.

Semiconductors help automobiles operate safely, advanced medical equipment save lives, and military radar systems detect dangers.



Market leadership in semiconductor design confers multiple advantages, including the following:

- **A Virtuous Cycle of Innovation.** Leadership in design supports a virtuous cycle of innovation. For example, design leadership has enabled firms in the US to attract and train a talented foreign-born workforce. The contributions and innovations of this workforce generate profits that companies can reinvest in R&D to drive continued expansion of the workforce and future innovations.

- **Greater Ability to Shape Standards.** In any technical domain, standards support interoperability and enable companies to more easily collaborate across the supply chain. Often, firms that lead in design are the first to develop products that require standards (as was the case with Wi-Fi, Bluetooth, and 5G wireless), and this enables them to play a leading role in reaching consensus on what standards are set and to rapidly develop expertise in optimal design for a given set of standards. Regions with many leading design firms will be at a relative advantage in setting and leveraging the benefits of technical standards.

- **Stronger Security.** Design leadership offers national security advantages in two dimensions. First, regions with design leadership have access to more advanced semiconductor chips that can give defense and weapons systems greater efficacy. Second, regions with design leadership may be at lower risk of malicious tampering and supply chain interdiction—for example, by protecting critical design information and enabling traceability and control of design IP.

- **Expanded High-Quality Employment.** Design leadership supports high-quality employment directly via high wages and indirectly via high employment multiples. For example, in 2020, the average annual income for US workers employed in semiconductor design was about $170,000 compared to a US median of about $56,000.

- **Advantage for OEMs in Adjacent Industries.** OEMs in technology-heavy industries rely extensively on semiconductors in the systems they design. Because collaboration within a shared geography and cultural context is often easier, OEMs can create competitive advantage by working directly with market-leading chip designers and employing practices such as co-design and system level optimization. (See the sidebar "OEMs That Benefited from Chip Design Leadership.")

OEMs That Benefited from Chip Design Leadership

Innovation leadership in semiconductor design yields innovations in multiple industries, thereby supporting broader economic growth and market leadership.

Autonomous Cars. Semiconductor designers and automakers can create and co-optimize chips to more efficiently process data from the sensors on a car. Custom-designed chips can also include critical safety features such as redundant power systems to ensure that chips operate safely and reliably in the most challenging environments.

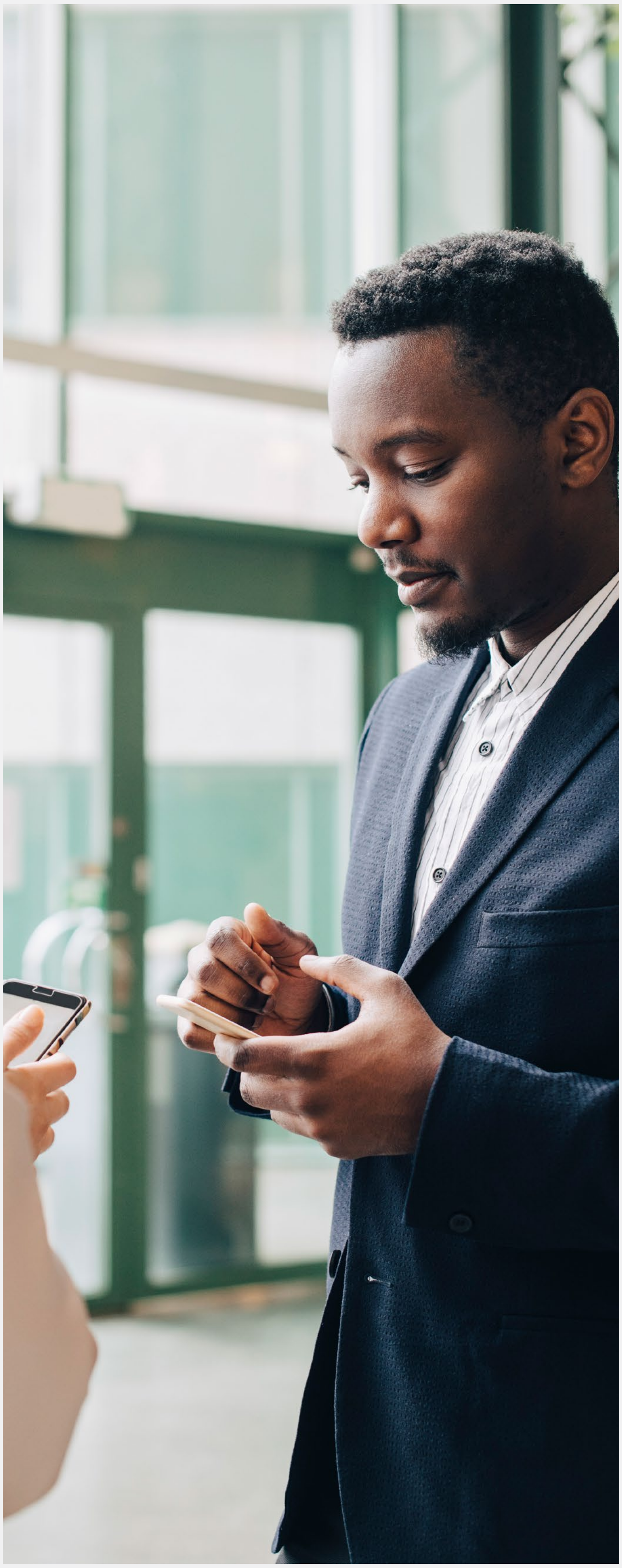
Smartphones. By working closely with OEM device engineers, chip designers can optimize their designs to meet the evolving system needs of the latest smartphones. For example, custom-designed chips can improve on-device AI performance, image processing, and power efficiency. By tightly controlling design tradeoffs at the system level, designers can create hardware and software systems with more innovative features and superior overall performance.

Cloud Computing. Designers create custom chips to meet specific cloud computing needs, from high-quality video streaming to efficient genomic analysis for COVID-19. Such chips help data centers optimize performance and lower power consumption. These benefits were clear in 2020 when fast cloud computing helped researchers and scientists rapidly sequence the genomes of COVID-19 variants.

5G Communications. Chip designers collaborate with other communications companies to optimize system performance. For example, chip designers work with network operators to tailor chips for network operators' cell towers and for equipment manufacturers' transceiver designs. By addressing these issues in tandem, mobile network operators can optimize the communications system more effectively and implement 5G more reliably.

Medical Devices. Medical devices such as implantable pacemakers and neurostimulators can be lifesavers. By designing custom chips, medical device makers can ensure that devices that must function in challenging physical circumstances—inside a human body, for example—can operate with ultralow power consumption, exceptionally high reliability, and maximum diagnostic usefulness.

National Security. Missile systems, aircraft, unmanned aerial vehicles, and radar systems rely on semiconductors. Chip design leadership enables the US defense industry to enhance existing and innovate new and superior defense systems that are critical to strengthening national security.



Design Leadership Is Not Guaranteed

Design leadership has shifted in the past and may shift again. In fact, since 1990, design leadership, as inferred from company revenues, has changed significantly in each decade. (See Exhibit 4.)

US semiconductor companies, which today are leaders in design, aren't sitting still. They have invested an estimated $40 billion in design-related R&D in 2021. Given the increased intensity of competition, however, the US is on a trajectory to grow more slowly than other regions and potentially cede market share. The US's overall market share (measured by overall chip sales revenue) has fallen steadily, from about 50% in 2000 to 46% in 2020, and a projected 36% by 2030.

To understand the likely outlook for 2030 market share, we modeled the flow of design engineers by geographic region, with the assumptions that revenue and market share are driven by R&D investment, and that R&D investment is driven by the availability of design engineers. We found that the US design workforce is likely growing at just above a replacement rate of less than 1% annually. In contrast, mainland China's design workforce is growing at 6% annually, and the relative productivity of its engineers is improving by 6% annually. The design engineering workforces in Europe, Japan, South Korea, and Taiwan are projected to grow at annual rates of 1% to 3%. Overall, the forecasted rapid growth of mainland China's semiconductor industry could result in a 14-percentage-point gain in market share, while US market share may decline by 10 percentage points.

The key factor contributing to this projected reduction in overall US market share is faster growth overseas, enabled by more favorable investment policies and workforce growth. This trend may restrict the relative ability of US-headquartered companies to reinvest, increasing the likelihood that leadership will shift to other regions. (See Exhibit 5 and "Semiconductor Design Workforce and Market Share Model" in the Appendix.)

Three Key Challenges Facing the US Semiconductor Industry

If the US semiconductor industry were to aim to defend its leadership position in design, three challenges would need to be addressed:

- **Challenge 1: Design and R&D investment needs are rising.** Each generation of semiconductors requires greater investment in design and R&D, including new EDA tools, IP, and process design kits, as well as semiconductor designs. Several regions provide more public support for these efforts than the US does, leaving US-based chip design companies at a disadvantage and contributing to the erosion of US market leadership.

Exhibit 4 - Design Leadership Is Volatile, with New Semiconductor Industry Leaders Emerging Each Decade

Top 10 semiconductor companies by revenue

	1990	2000	2010	2020	2030
1	NEC	Intel	Intel	Intel	
2	Toshiba	Toshiba	Samsung	Samsung	
3	Hitachi	NEC	Toshiba	SK Hynix	
4	Intel	☆ Samsung	Texas Instruments	Micron	
5	Motorola	Texas Instruments	Renesas[1]	Qualcomm	Leadership to be determined
6	Fujitsu	Motorola	☆ SK Hynix	☆ Broadcom	
7	Mitsubishi	☆ STMicroelectronics	STMicroelectronics	☆ Nvidia	
8	Texas Instruments	Hitachi	☆ Micron	Texas Instruments	
9	Philips	☆ Infineon	☆ Qualcomm	☆ Apple	
10	Matsushita	Philips	Elpida[2]	Infineon	
Dropped out of top 10:		• Fujitsu • Mitsubishi • Matsushita	• Motorola • Hitachi • Infineon • Philips	• Renesas • STMicroelectronics • Elpida	

US
Japan
Europe
South Korea
Taiwan
☆ = New entrant in top 10

Sources: IC Insights; BCG analysis.

Note: Ranking based on global semiconductor sales excluding pure-play foundries. This exhibit is meant to illustrate the volatility of design market leadership and does not imply that only the top 10 companies by revenue are important to semiconductor design.

[1]Post NEC/Renesas merger.

[2]Combination of NEC, Hitachi, and Mitsubishi DRAM business.

- **Challenge 2: The supply of design talent is dwindling.** Semiconductor design requires highly skilled workers with specialized expertise. US chip design companies compete for them with other technology companies inside and outside the semiconductor industry in the US, and with chip design companies in other regions that are eager to win back their most talented nationals.

- **Challenge 3: Open access to global markets is under pressure.** The free flow of semiconductors across global markets is under pressure from factors such as tariffs and export restrictions, threatening US companies' ability to achieve the scale and profits needed to fund investment in ever-costlier next-generation design and R&D.

The global semiconductor design industry has delivered important innovations for decades. Advances in semiconductor design will continue, whether or not the US takes action to preserve market leadership for US-headquartered firms.

Addressing these challenges, which we detail in the next three sections of this report, will increase the likelihood that future innovations in semiconductor design are led by companies headquartered in the US.

Challenge 1: Design and R&D Investment Needs Are Rising

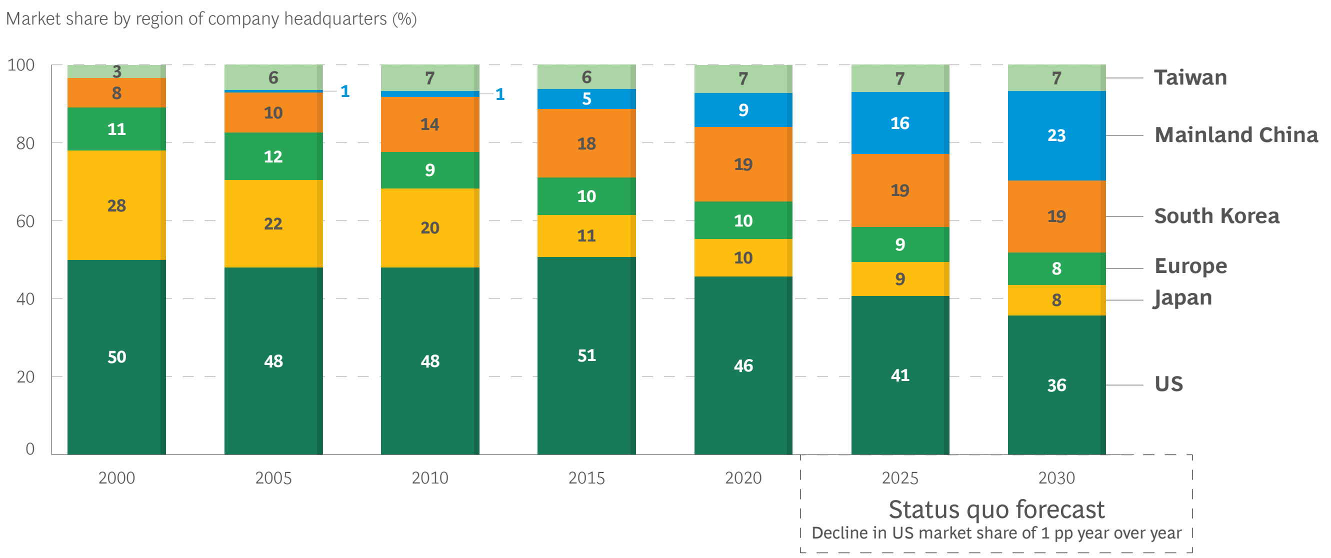
Between 2006 and 2020, the cost of designing a new chip on the latest manufacturing node has increased by a factor of more than 18. (See Exhibit 6.) This increase has created a drag effect on new chip designs, creating opportunities for new entrants and existing nonleading players to catch up and expand their market share.

The US private sector has responded by continually expanding its investments in design and R&D, but corresponding US public sector support lags that of other regions in funding for basic research and direct tax incentives.[5]

Funding for Basic Research

Over the years, US government funding of high-risk basic research has been critical to advances that have profoundly affected daily life (for example, antibiotics, the internet, and satellite communications). Governments typically fund research that is too distant, too uncertain, or too difficult for a single firm to turn into a competitive advantage.[6] While private industry has dramatically increased its funding of R&D in recent decades, public funding in the US has remained flat at 0.03% of GDP, even as other regions have expanded their public investments.

Exhibit 5 - The Market Share of US Companies Has Fallen Since 2000 and Is Projected to Drop to 36% by 2030

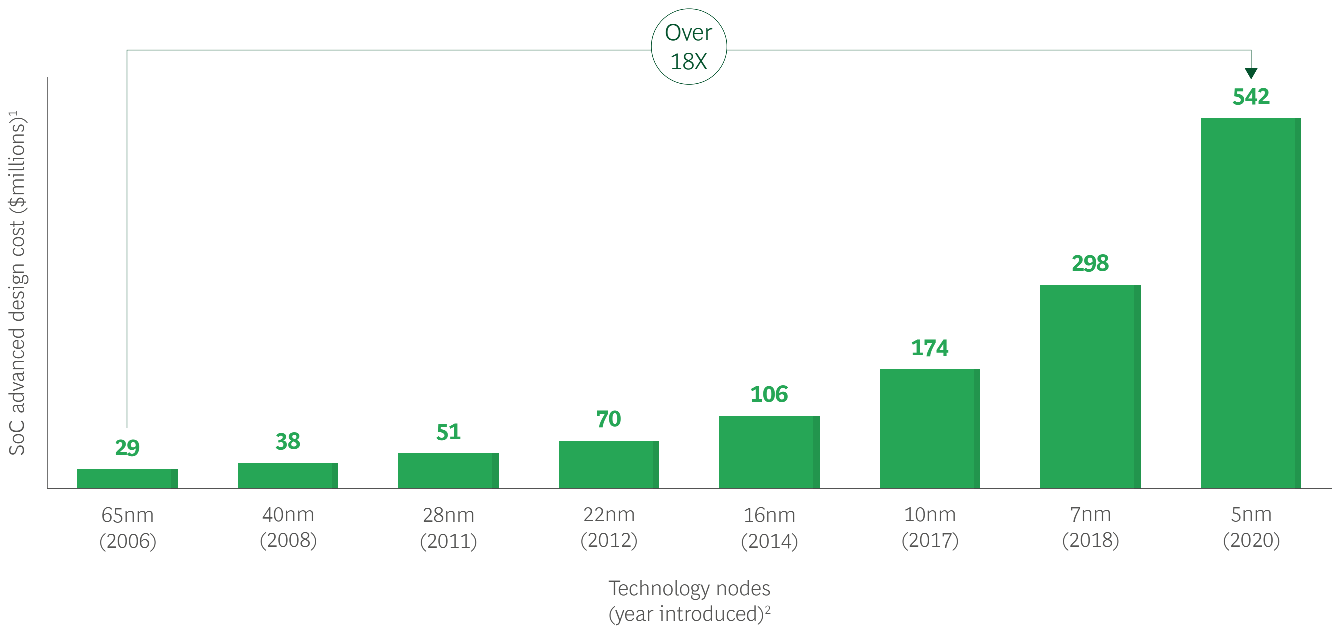


Sources: WSTS data; SIA; BCG analysis.

Note: Market share is based on revenues and the region in which headquarters is located for the company responsible for final sale of finished semiconductors; includes fabless and IDM revenues; foundry and outsourced semiconductor assembly and test (OSAT) revenues are excluded to avoid double-counting. Market share projections are modeled on the basis of the flow of design engineers by geographic region, with the assumptions that revenue and market share are driven by R&D investment and that R&D investment is driven by the availability of design engineers. Because of rounding, not all bar segment totals add up to 100%. pp = percentage point.

5. Published by the Semiconductor Research Corporation (SRC), the Decadal Plan for Semiconductors is a technical roadmap for the industry, outlining possible investments related to semiconductor design and R&D over the coming decade.
6. Consider the example of extreme ultraviolet lithography (EUV), a technology used in chip manufacturing. Initial research into this technology began in the 1990s. Public investment continued for decades until private industry took over development. Today, EUV is used in the manufacturing processes for many advanced chips.

Exhibit 6 - Design Costs Are Rising with Each New Technology Node



Sources: IBS; AnySilicon; TSMC.

¹System-on-a-chip (SoC) advanced design costs include intellectual property qualification, architecture, verification, physical, software, prototype, and validation activities.

²Year in which a technology node began volume production.

The US, mainland China, Taiwan, South Korea, and the EU have all recently announced plans to fund the expansion of domestic semiconductor capabilities—with a subset of these plans supporting design capabilities. (See Exhibit 7.) The plans encompass support for traditional basic research (such as precompetitive research within a university) and for commercial development (such as equity investments in semiconductor companies). Investments in both areas strengthen the pipelines of talent and innovation that are critical to leadership in design.

Despite these increased investments, however, the overall share of semiconductor-specific design and R&D funding in the US by public investment—comprising direct public R&D funding, tax incentives, and other recent initiatives—is 13%. In contrast, the share of semiconductor-specific design and R&D funded by public investment across Europe, Japan, mainland China, South Korea, and Taiwan is 30%. (See Exhibit 8.)

Tax Incentives

R&D tax incentives motivate private sector companies to increase their R&D expenditures. The US provides an average cumulative R&D tax incentive of 9.5% across federal, state, and local programs, which is below the median of a comparison set of regions.[7] (See Exhibit 9.)

In the US, these government incentives are usually available to all industries, but other regions have adopted incentives that are specific to the semiconductor industry, including incentives for design:

- South Korea recently established a "core strategy technology" track that allows tax deductions of up to 50% for semiconductor R&D.
- Mainland China has exempted key design companies from corporate income tax for five years after their first profitable year and imposes a reduced tax rate of 10% after that.
- The Indian government, as part of its Design Linked Incentive program, plans to scale up support for domestic semiconductor design by providing incentives of up to 50% of eligible R&D expenditures.

Since people perform most design activities, it is easier to move these activities across borders than, for example, to move a physical manufacturing facility. By providing more direct support for design-related R&D through a design incentive, the US could help stem its loss of design share by encouraging both US and non-US companies to expand or build design centers within the US.

7. The comparison set includes Organization for Economic Cooperation and Development (OECD) regions with populations exceeding 4 million, as well as Brazil, Russia, India, and mainland China.

Exhibit 7 - Several Governments Have Funded Expansion of Local Semiconductor Design Capabilities

Europe

EU-funded European Processor Initiative to design and build a family of high-performance, low-power processors

The EU's European Chips Act seeks to reinforce Europe's capacity to innovate in the design, manufacture, and packaging of advanced chips

India

Government approved a **$600 million** Design Linked Incentive program for semiconductors, providing preferential tax treatment for design activities

Mainland China

National Integrated Circuit Investment Fund invests **$3 billion** in design

Revamped stock market rules to establish STAR Market, on which fabless firms have raised over **$50 billion** through IPOs

South Korea

Government pledged **$1.3 billion over ten years** for AI and power chip design

Taiwan

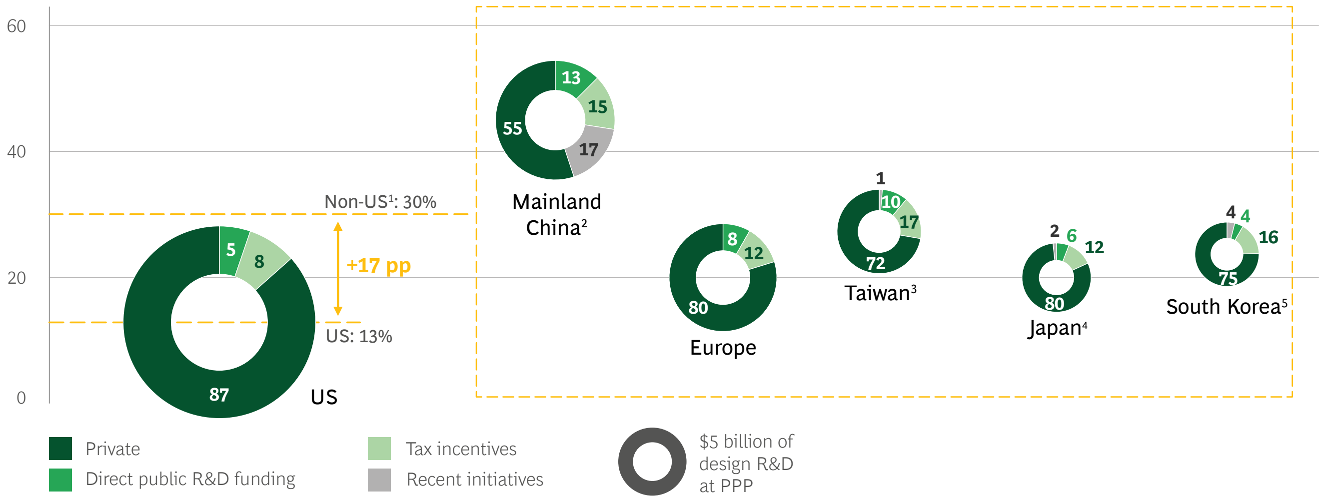
Government will provide **$300 million over seven years** for semiconductor R&D

Sources: Various press releases and government announcements; BCG analysis.

Note: Regions are listed alphabetically. Plans listed are not exhaustive.

Exhibit 8 - The Share of Semiconductor-Specific Design and R&D Funded by Public Investment Varies by Region

Estimated share of semiconductor-specific R&D funded by public investment (%)
(includes estimates from recently announced initiatives)



Sources: OECD national accounts data and ITIF; government websites; SIA; BCG analysis.

Note: pp = percentage points; ppp = purchasing power parity. Because of rounding, not all circle percentages add up to 100%.

[1] Includes mainland China, Europe, Taiwan, Japan, and South Korea.

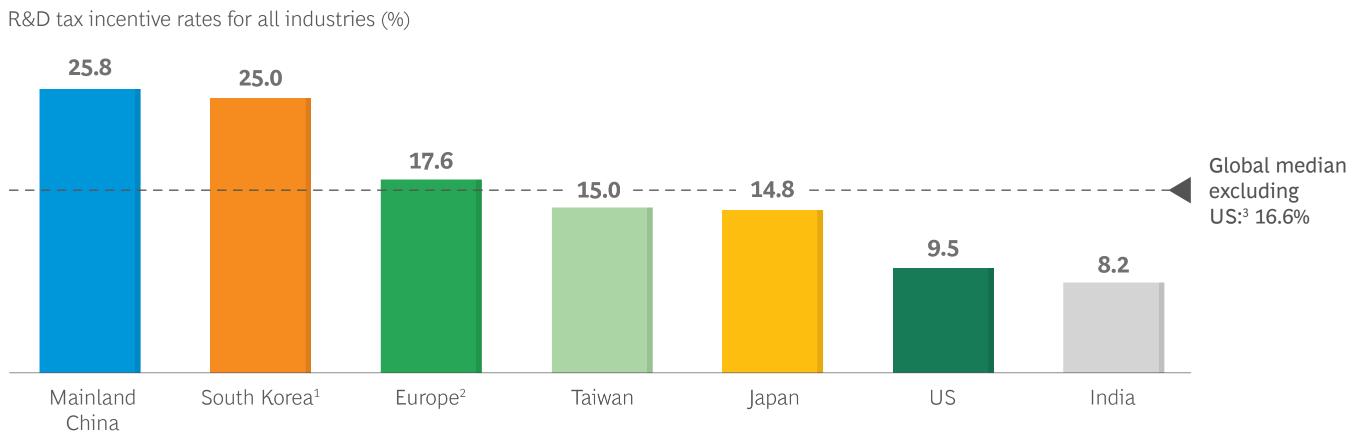
[2] Includes elimination of 25% corporate income tax for semiconductor design.

[3] Includes $300 million over seven years for foreign companies to establish R&D centers.

[4] Includes recent initiatives such as the Post 5G Fund and the Green Innovation Fund.

[5] Includes recent initiatives such as K-semiconductor belt strategy and AI R&D programs.

Exhibit 9 - R&D Tax Incentive Rates Vary Considerably in Different Regions



Sources: ITIF; SIA; BCG analysis.

Note: Tax incentive rates are provided under the user cost of capital framework as promulgated by the Information Technology and Innovation Foundation (ITIF); data includes income- and expenditure-based measures and impact of federal, state, and local R&D tax incentives.

[1]R&D tax incentives in South Korea vary and can be up to 50% for certain R&D expenditures conducted by small and medium-size enterprises in select industries; the rate shown for South Korea applies to qualifying current-year R&D expenditures for small and medium-size enterprises.

[2]Based on a simple average of rates in 20 European countries for which data is available: Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, and the UK.

[3]Median of 33 countries analyzed by ITIF.

Challenge 2: The Supply of Design Talent Is Dwindling

In 2021, US-headquartered companies employed approximately 94,000 of the world's estimated 187,000 semiconductor design engineers. Of that number, about 60% were physically located in the US, and about 40% were physically located abroad. (See Exhibit 10.)

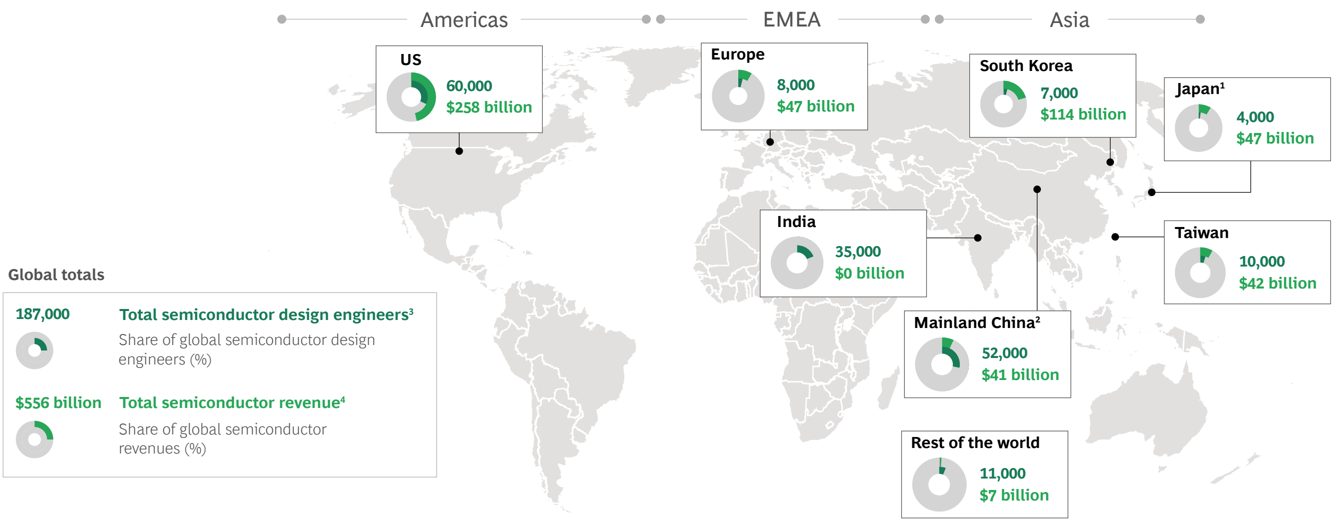
Although US-headquartered companies will undoubtedly continue to take advantage of the global talent pool, most companies' core nexus for design innovation exists at domestic sites. Consequently, to maintain design leadership, US-headquartered companies must grow their US-based workforces.

To better understand these dynamics, we took a bottom-up view of the design workforce, considering the workforce's current size, the different skills needed, the current distribution of talent globally, inflows from universities, and outflows (in the form of retirement, industry changes, and departure of foreign-born talent from the US).

Our analysis found that on average, from 2021 to 2030, US universities will train and graduate nearly 156,000 students each year with undergraduate or graduate degrees in fields that could, in principle, translate into careers in semiconductor design—for example, degrees in electrical engineering (EE) or computer science (CS). Of this number, about 2% will enter the design workforce each year, which amounts to approximately 3,300 new hires in an average year. Largely offsetting this hiring will be annual industry- or field-level attrition of about 2,650 workers—or roughly 4% of the design workforce—through retirement (60% of attrition), emigration (23%), and career changes (17%). (See "Semiconductor Design Workforce and Market Share Model" in the Appendix.)

Exhibit 10 - Nearly One-Third of the World's Semiconductor Design Engineers Are Based in the US

Estimated location of semiconductor design engineers from top global companies, 2021



Sources: SIA Factbook 2022; BCG analysis.

Note: Total number of design-related positions are approximated on the basis of publicly available profiles in LinkedIn for top fabless and IDM players as well as OEMs. Numbers for Mainland China, India, and Taiwan are augmented with additional government data and industry benchmarks. Numbers may be underestimated due to incomplete availability of publicly available data. EMEA = Europe, Middle East, and Africa.

[1]Japan design workers are calculated as design workers working in Japanese companies but not necessarily located in Japan.

[2]Includes all members of the R&D workforce employed by local fabless companies.

[3]Unless otherwise noted, this total excludes engineers engaged in manufacturing-related R&D.

[4]Based on company HQs, as of 2021.

As a result, net growth of the US design workforce will be less than 1% per year, and we estimate that the US-based design workforce will have grown to about 66,000 engineers by 2030. As the semiconductor market grows, however, maintaining the current US market share of 46% would require a domestic design workforce of about 89,000 engineers. The shortfall of approximately 23,000 engineers (25% of the required workforce) would consist of about 90% bachelor's-level or master's-level engineers and about 10% PhD-level engineers. (See Exhibit 11.)

Some of this talent gap can be filled via productivity improvements, but in the bigger picture, avoiding a serious shortfall in talent requires increasing inflows of science, technology, engineering, and mathematics (STEM) graduates into semiconductor design and increasing retention of existing talent, including women and underrepresented minorities.

STEM Graduates

Historically, US colleges and universities have offered the world's best STEM programs. The US is home to approximately half of the world's top university programs in EE and CS, the disciplines most relevant to semiconductor design. Through programs like these, the US has played an important role in educating and training both US citizens and foreign nationals in semiconductor design.

Today, however, only around 19% of students pursuing degrees in the US are focusing their studies on STEMrelated fields, compared with 40% in mainland China, 32% in India, 30% in South Korea, and 23% in Western Europe. Moreover, US university enrollment in these areas relies to a large extent on foreign nationals, who represent 28% of all students in US EE and CS programs, and 65% of all students in EE and CS graduate programs. (See Exhibit 12.)

Compounding this gap in engagement, other regions are expanding their investments in STEM education, as the following examples indicate:

- In 2008, South Korea established Meister schools, a new type of vocational high school focused on the semiconductor industry, with curricula tailored to local semiconductor industry needs, industrial internships incorporated into student plans, and faculty that include industry experts.
- In 2017, mainland China added STEM to its primary-school curriculum. The following year, the government launched the China STEM Education 2029 Innovation Action Plan to increase students' access to STEM education. In addition, the Ministry of Education created IC doctoral programs at 19 universities.
- In 2019, Taiwan's ministry of education announced a plan to increase funding for STEM education in its K-8 and 9-12 schools.
- Japan has established a legal requirement that the government refresh its STEM education plan every five years to support science, technology, and innovation.

Although a full evaluation of education policy options is beyond the scope of this report, we note two potential high-level courses of action. First, the US can work to increase the number of students pursuing studies in relevant STEM fields, including EE and CS. Second, the US can work to increase the number of EE and CS graduates who choose to pursue careers in semiconductor design.

To increase the number of students engaged in EE and CS studies, the US could work on broadening general interest and improving access—for example, by funding additional K-12 STEM education, promoting stronger inclusion of women and underrepresented minorities, providing additional funding for college scholarships in EE and CS, or offering loan forgiveness for students who pursue careers in semiconductor design. (See SIA's comments in response to a request for information on the national STEM strategy.)

To increase the number of EE and CS students who go on to pursue careers in design, policymakers could increase tax incentives for domestic R&D, thus effectively creating a job credit; provide design-related research fellowships similar to existing National Defense Science and Engineering Graduate (NDESG) and National Science Foundation (NSF) fellowships, which fund PhD studies; or provide targeted loan forgiveness for students who enter the design workforce. The US could also take steps to ensure the world's best and brightest students—including those from other regions who trained at US universities—can readily enter the US design workforce. Region-level immigration quotas have created a backlog of highly skilled workers who would like to work in the US but are unable to do so.

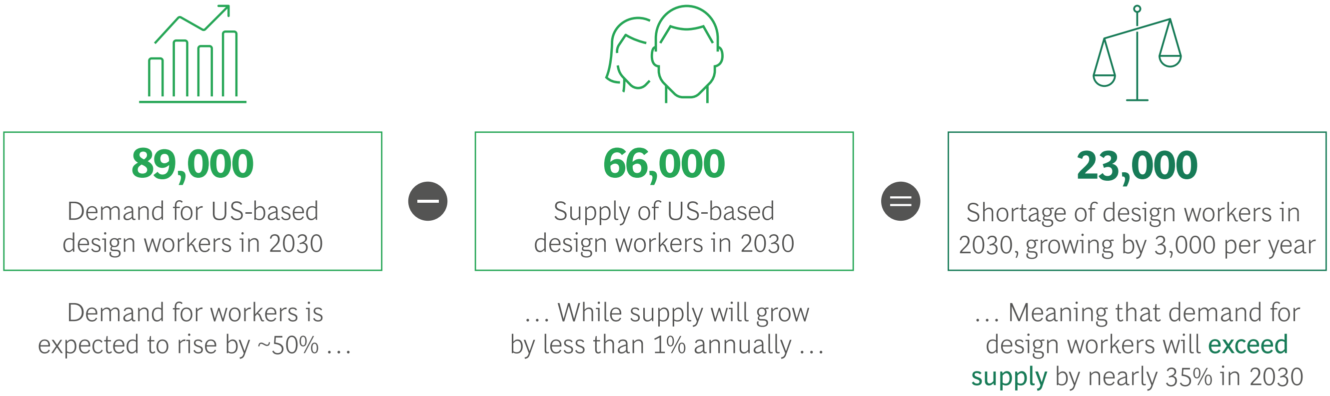
The cost of these programs would vary. However, assuming an average debt load of $25,000 per student at the MS/BS level and a total program cost of $200,000 at the PhD level, closing the talent gap would require at least $1 billion in direct funding through 2030, an amount equivalent to about 1.2% of NSF funding, if FY2022 funding levels are maintained through 2030. If the US government were to provide funding, coordinated action from universities and employers would be essential. For example, institutions would need to maintain quality as programs scaled, and employers would need to be proactively involved in the education and training of students. Taken together, these efforts would increase the profile and attractiveness of design-related careers.

Experienced Engineers

Each year, about 2% of design engineers exit the US design workforce. Approximately 40% of these individuals leave to pursue opportunities in other industries, while 60% leave to take jobs—including in design—outside the US. The private sector must take primary responsibility for retaining engineers who leave the design workforce each year but remain in the US.

At the same time, however, the public sector has a large and low-cost opportunity to bolster the design workforce by encouraging inflows of semiconductor design engineering talent from outside the US—for example, by increasing or eliminating regional quotas on highly skilled workers' eligibility for permanent immigration. Retaining workers who leave the US could roughly double the baseline growth rate of the design workforce and meaningfully contribute to closing the domestic talent gap.

Exhibit 11 - The US Semiconductor Design Industry Is on Track to Face a Shortfall of 23,000 Highly Skilled Workers by 2030

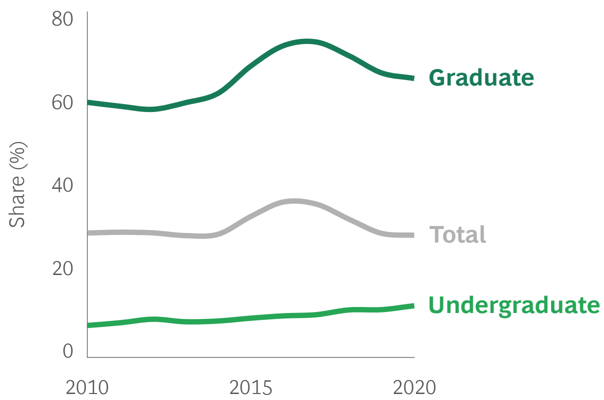


Source: BCG analysis.

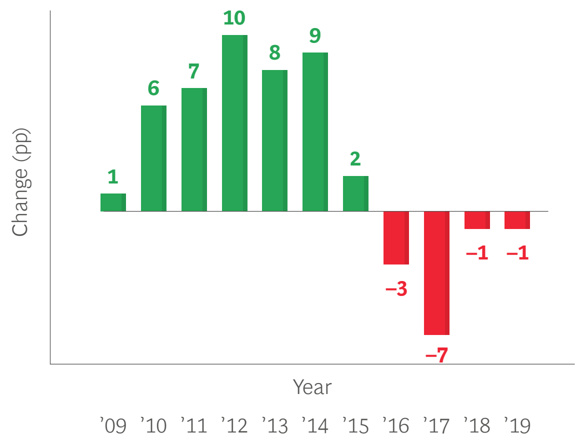
Note: Numbers are rounded for clarity and display purposes. For additional information, see "Semiconductor Design Workforce and Market Share Model" in the Appendix.

Exhibit 12 - US Semiconductor Design Companies Rely Heavily on International Students, Whose Enrollment Numbers Are Declining

Share of international students
(Electrical engineering and computer science)



Annual change in new international student enrollment



Sources: Shanghai Ranking; IIE, "New International Student Enrollment: International Student Data from the 2020 Open Doors Report."

Note: pp = percentage points.

Challenge 3: Open Access to Global Markets Is Under Pressure

US design companies have long benefited from open access to global markets. (See *How Restricting Trade with China Could End US Semiconductor Leadership*.) Such access enables design companies to work with specialized partners in other regions and design better semiconductors for end customers.[8] Global markets, in conjunction with IP protections, also provide a large customer base that US design firms can use to gain scale and generate profits that they can then reinvest in design and R&D. Put simply, open access to global markets and partners is an important component of the virtuous cycle of innovation. (See Exhibit 13.)

As geopolitical tensions rise, however, free and open trade is subject to challenges in the form of tariffs, export controls, and industrial policy. As we noted in 2020, “Broad unilateral restrictions on … access to US technology would significantly deepen and accelerate US companies’ [design] share erosion”—thus undermining reinvestment in R&D. Trade restrictions have profoundly negative repercussions for the semiconductor industry in the US and globally, harming all participants.

For example, today’s US export restrictions have encouraged China to find alternative sources of semiconductor design. (See the sidebar “The Growing Semiconductor Design Ecosystem in China.”) Chinese OEMs are responsible for 27% of global semiconductor demand (second only to the US’s 34%) and are the most important non-US market for semiconductors. (See Exhibit 14.) As a direct result of US export restrictions, non-US OEMs are increasingly turning to locally designed semiconductors.

If the EU, India, Japan, South Korea, mainland China, and other regions increasingly seek to localize elements of the semiconductor value chain, there is a real risk that large global markets will become balkanized by subscale local champions, to the detriment of all participants.

Exhibit 13 - R&D Is Part of a Virtuous Cycle of Innovation That Supports Technology Leadership in the US

Superior R&D intensity

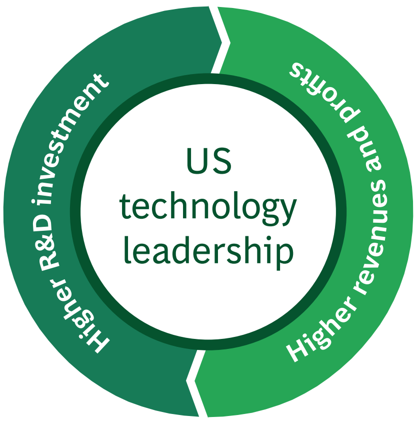
18% US R&D spending as a percentage of revenue

2X Higher than the rest of the world

Superior scale

$208 billion US semiconductor revenue

2X More than second-leading region



Superior market share

46% US global share

2X The size of US domestic demand

Superior profit margins

59% US semiconductor gross margin

+11 pp Higher than the rest of the world

Source: BCG analysis, using data from SIA, company reports, and BCG ValueScience Center.

Note: All numbers are for 2020. Revenue figures reflect weighted averages of reported financial data from top companies in each region. pp = percentage points.

8. Examples of specialized partners include manufacturers of specialized equipment, suppliers of materials, foundries, and other companies in the value chain that help designers reach end customers.

The Growing Semiconductor Design Ecosystem in China

Since 2017, mainland China's design industry growth has been driven primarily by the rise of increasingly competitive Chinese fabless design firms, which now account for 16% of global fabless semiconductor sales. From 2017 to 2020, the revenue of the top 25 Chinese fabless companies doubled, from $12.2 billion to $24.4 billion. (See the exhibit.) Venture capital investment in Chinese semiconductor companies grew more than 366% from 2019 to 2020, with approximately 70% of deals flowing to design companies.

At least in part, this accelerated growth is a result of US efforts to restrict access to its market by Chinese OEMs, leading those OEMs to try to build resilient domestic supply chains—an effort reinforced by Chinese government industrial policy. Government incentives—including direct R&D investment grants, VAT rebates, capital expenditure support, and exemption from corporate income taxes—have encouraged growth of the domestic semiconductor ecosystem in China.

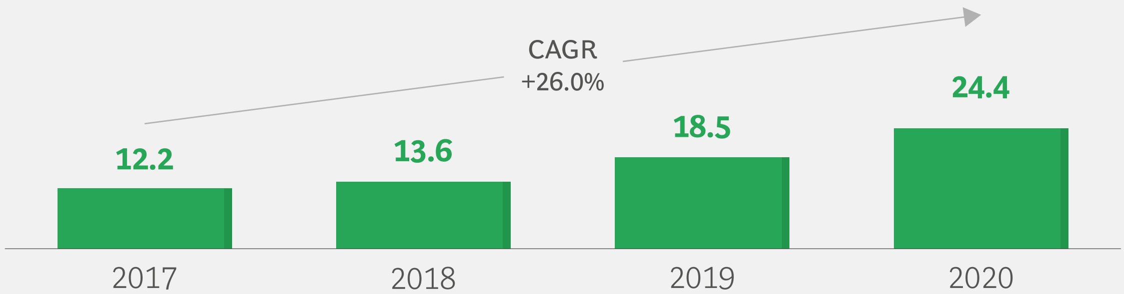
Realizing their criticality, both the Chinese government and Chinese industry are accelerating investments in domestic alternatives to foreign electronic design automation (EDA) tools, core intellectual property (IP), and manufacturing. China's National Integrated Circuit Industry Investment Fund has invested $125 million in EDA and IP firms. In 2021, 12 Chinese EDA companies in mainland China raised more than $310 million, a 54% increase from the corresponding 2020 figure. State-backed funds have also invested more than $2 billion into Semiconductor Manufacturing International Corporation, mainland China's largest domestic foundry.

Chinese companies are investing in domestic chip design resilience, too. In 2021, AI chip (including GPU and HPC) companies—dozens of which were founded in the past five years—raised $4.5 billion in total funding across multiple financing rounds via 92 transactions. In addition, Chinese companies are adopting and promoting open-source design technologies such as RISC-V to avoid dependency on technologies that might be subject to export restrictions.[1]

Increasingly, China's large OEMs are engaging in chip design to develop potential alternatives to the server chips sold by US companies. For example, Alibaba recently announced the development of a server CPU based on advanced RISC machine (ARM), which it could deploy to its data centers, reducing its reliance on foreign semiconductors.

The Revenue of the Top 25 Chinese Fabless Companies Doubled, from $12 Billion in 2017 to $24 Billion in 2020

Revenue of the top 25 Chinese fabless companies, by revenue for the top 25 companies in each year, 2017–2020 ($billions)

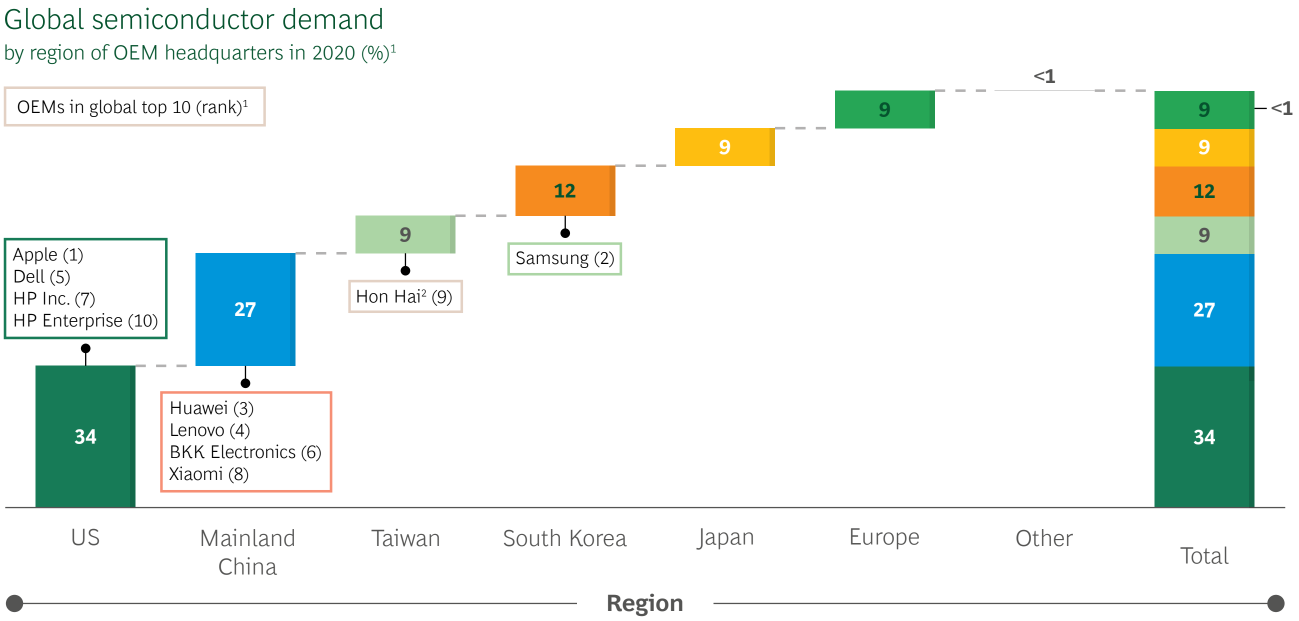


Source: SIA estimates, via official company financials.

Note: The specific list of top 25 companies varies from year to year; revenues for HiSilicon—which is a privately held, wholly owned subsidiary of Huawei and is the largest Chinese fabless firm in each of these years—are estimated.

1. Open-source technologies like RISC-V are a common resource that all companies can use to create their own products. As these technologies develop, they provide a rising "floor" off of which companies can build.

Exhibit 14 - OEMs in the US and China Are Responsible for More Than 60% of Global Semiconductor Demand



Source: Charts/graphics created by BCG based on Gartner research. Source: Gartner®, "Tool: Semiconductor Spending by Customer, 2020," Masatsune Yamaji, 16 April, 2021. Gartner is a registered trademark and service mark of Gartner, Inc. and/or its affiliates in the US and internationally and is used herein with permission. All rights reserved.

[1]Rank of OEMs in the global top 10 is based on global revenues in 2020 for all semiconductor devices.

[2]Hon Hai Precision Industries, also known as Foxconn, is both an OEM and a contract manufacturer.

If the US Aspires to Sustain Its Design Leadership, Public Investment and Incentives Would Go a Long Way to Catalyze Upward Momentum

For the past three decades, the US's leadership in semiconductor design has contributed significantly to the nation's GDP (approximately $120 billion in 2020), created high-skilled jobs (approximately 173,000 in 2020), and provided a range of other benefits—from greater critical infrastructure security to advantages for domestic OEMs in adjacent industries. But US design leadership and its attendant benefits are not inevitable.[9]

Regardless of what the US government or US companies do, the semiconductor industry will grow, and semiconductor design will continue to occur in the US and abroad.

To maintain its leadership in design, the US must have sufficient private and public investment and a large enough workforce to maintain a market share that enables a virtuous cycle of reinvestment. Without action in these dimensions, US firms engaged in design activity are on a trajectory to lose an estimated cumulative $450 billion in sales over the next ten years through market share erosion.[10]

9. GDP contribution is measured as of 2020. US design semiconductor GDP impact is calculated based on its share of the total semiconductor workforce and is based on the GDP analysis in *Chipping In*, a May 2021 report from SIA and Oxford Economics.

10. US market share may decline by 10 percentage points through 2030, resulting in a potential revenue loss of $450 billion over ten years. Market share projections are modeled on the basis of the flow of design engineers by geographic region, with the assumptions that revenue and market share are driven by R&D investment and that R&D investment is driven by the availability of design engineers.

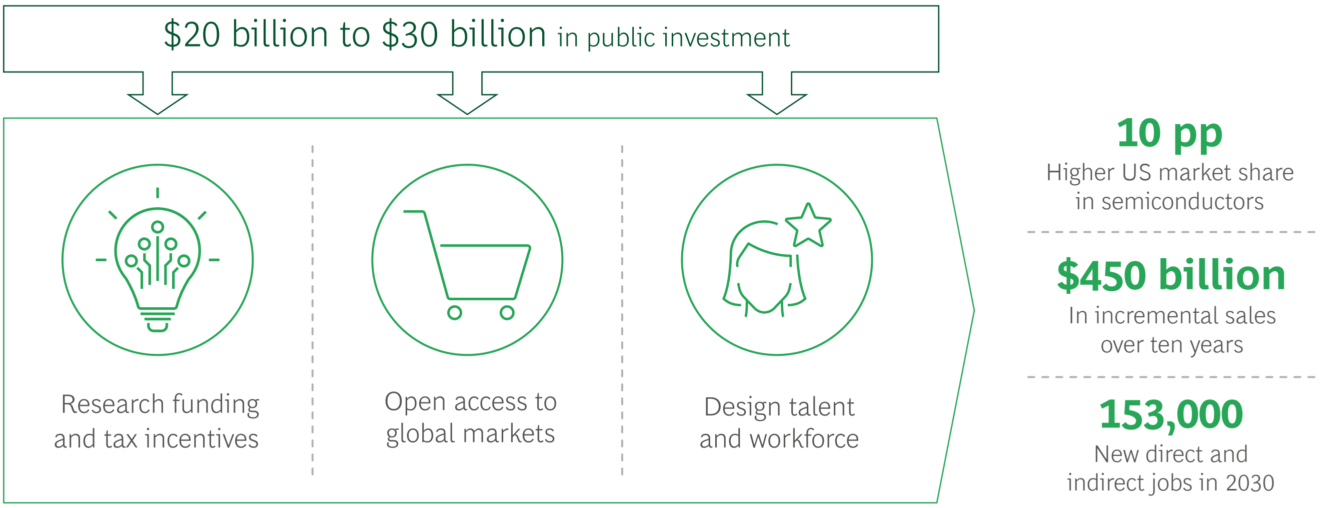
As a starting point, given current trends, the private sector is expected to invest at an aggregate rate of $400 billion to $500 billion in design R&D over the next ten years. To complement this commitment, the US government would need to invest an incremental $20 billion to $30 billion in tax incentives and direct funding for public R&D (equivalent to about 4% to 6% of private sector investment or roughly 40% to 50% of the gap between current levels of US support and average support in other regions).[11] A typical mix would deliver approximately two-thirds, or $15 billion to $20 billion, of public investment via a design tax incentive.

Solving the emerging workforce problem will entail taking action on two fronts: making investments in STEM education and increasing the flow of talent from outside the US to train approximately 23,000 additional design engineers. Although different policy approaches would have different costs, the cumulative cost of filling this gap through end of the decade could be as little as about $1 billion.

From this investment, US-headquartered design companies would generate approximately $450 billion in incremental sales, 23,000 direct jobs in engineering, and 130,000 indirect and induced jobs in other fields, and they would fortify the US's leadership position in semiconductor design.[12] (See Exhibit 15 and "Return on Public Investment in Semiconductor R&D Model" in the Appendix.)

The semiconductor industry is attracting strong interest from policymakers. As governments and companies around the world make significant investments in the sector, innovation in semiconductor design is sure to continue. Public investments that address the challenges discussed in this report increase the likelihood that future design innovations will happen domestically and help preserve the benefits of design leadership that the US enjoys today.

Exhibit 15 - Public Investment in Semiconductor Design Can Grow Sales, Create Jobs, and Fortify US Leadership in Semiconductor Design



Source: BCG analysis.

Note: Market share and jobs impact is sized as of 2030; sales impact is sized over ten years. pp = percentage points.

11. Assuming an R&D intensity of $6 of revenue per $1 of R&D, approximately $75 billion of incremental design R&D is needed to prevent US share erosion over the next ten years.

12. The estimate of indirect and induced jobs cited here is based on analysis of employment multiples in *Chipping In*, a May 2021 report from SIA and Oxford Economics.

Appendix

Key Semiconductor Design Technologies

There are three major categories of semiconductors *(see Strengthening the Global Semiconductor Value Chain in an Uncertain Era)*:

- **Logic semiconductors** are integrated circuits that serve as the fundamental building blocks or "brains" of computing. This category spans both advanced logic and more mature logic, which together encompass microprocessors, microcontrollers, and other technologies that permit the execution of computing operations.

- **Memory** stores the instructions, algorithms, and data needed for operation and is deployed in all integrated circuit applications. Since data storage requirements increase exponentially with advances in IoT, AI, and edge computing, memory capacity and bandwidth are becoming gating factors and require continuing innovation.

- **Discrete, Analog, and Other (DAO) semiconductors** transmit, receive, and transform information dealing with nonbinary parameters such as temperature and voltage. Discrete products include diodes and transistors that are designed to perform a single electrical function. Analog products translate analog signals such as voices into digital signals and support many power management functions. This category also includes optical and non-optical sensors.

Within these categories, companies often specialize in designing a subset of specific semiconductor types. Partly as a result, the revenue market shares controlled by different regions vary across product segments. Although regional market share is concentrated in advanced processors, for example, regional market share is more diffuse in non-optical sensors. (See the exhibit.)

Semiconductor applications may require chips from more than one of the broad categories described above. Many mobile phones, for example, have almost as much DAO content (essential for features such as cellular connectivity, camera functionality, and power consumption management) as logic content (which includes microprocessors that provide increasing computing power with every new phone generation) and memory (for storage of digital content on the device).

Summary of the Semiconductor Value Chain

As discussed in *Strengthening the Global Semiconductor Value Chain in an Uncertain Era,* the semiconductor value chain is complex and global. Each activity in the value chain requires differing levels of R&D investment and capital expenditures; consequently, each activity is responsible for a varying share of the overall value generated through the value chain.

Precompetitive Research

A key input for both semiconductor design and manufacturing, precompetitive research is typically basic research in science and engineering performed by a global network of scientists from industry, universities, government-sponsored national labs, and other research institutes. Frequently supported by governments and universities, precompetitive research often yields findings that are published and shared broadly, in contrast to proprietary research and development. For example, the US Department of Defense's Microwave and Millimeter Wave Integrated Circuit (MMIC) program in the late 1980s conducted research into new materials—such as gallium arsenide—for use in military systems. Today, multiple companies use gallium arsenide–based semiconductors for other applications, such as to enable smartphones to establish wireless communication links with cell towers.

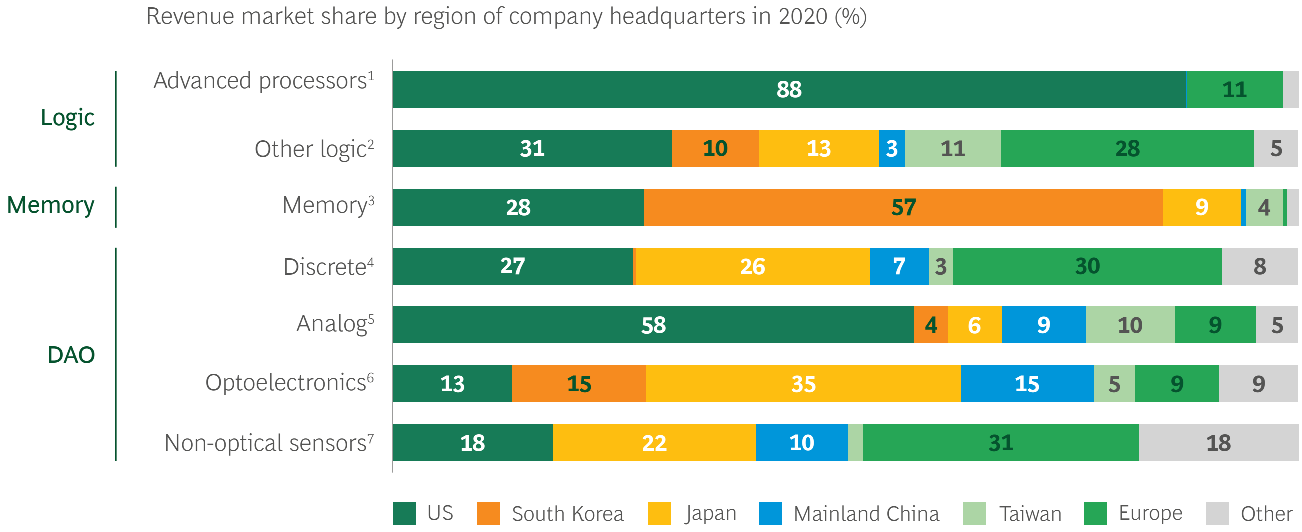
Design

For a detailed discussion of this topic, (See "Design Is a Critical Part of the Semiconductor Value Chain.")

Electronic Design Automation (EDA) and Core IP

Semiconductor chip design and production relies on electronic design automation (EDA) software tools and flows throughout the microelectronics supply chain, from initial architectural studies, implementation, verification through manufacturing, yield learning, packaging, and life-cycle management. EDA companies are trusted intermediaries between design companies and foundries. Further, semiconductor designers make extensive use of preexisting building blocks of intellectual property (IP) for common components such as processors, standard cells, memories, and process-specific analog mixed-signal interface blocks. EDA tools and IP must be enabled—that is, tailored to a specific foundry and process. Three areas are critical for semiconductor design enablement:

The US Leads in the Design of Logic—Especially Advanced Processors—but Lags in Optoelectronics and Other Sensors



Source: Charts/graphics created by BCG based on Gartner research. Source: Gartner®, "Market Share: Semiconductors by End Market, Worldwide, 2020," Andrew Norwood et al., 31 March 2021.

Note: Regional market share calculations are based on revenues of the final company to sell the finished semiconductor. DAO = discrete, analog, and other. Because of rounding, not all bar segment totals add up to 100%.

[1]Includes CPUs, GPUs, DSPs, discrete application/multimedia, and FPGA/PLD.

[2]Includes microprocessor embedded, microcontroller 32-bit, microcontroller 16-bit, microcontroller 8-bit display driver, and other logic.

[3]Includes DRAM, emerging memory, other memory, flash memory, and NAND.

[4]Includes transistors, other discretes, and diodes.

[5]Includes voltage regulator/reference, power management, wireless connectivity, discrete cellular baseband, RF front-end and transceivers, integrated baseband/application processor, wired connectivity, data converter/switch/multiplexer, other application specific, and other analog.

[6]Includes image sensor – CMOS, image sensor – CCD, other optoelectronics, photosensor, LED, coupler, and laser diode.

[7]Includes magnetic sensors, other sensors, MEMS microphones, fingerprint sensors, environmental sensors, and inertial sensors.

- **Design Tools.** Such tools are enabled for a specific foundry, technology node, and process design kit (PDK). A foundry may have a dozen or more process technologies or variants.

- **Third-Party IP Building Blocks.** These building blocks are tailored for compatibility with each foundry's specific PDK as well as any extensions for low leakage, radio frequency, extreme environments, and so on. As such, they are critical starting points for designers to implement their designs.

- **Reference Platforms.** These systems carefully combine EDA tools and IP to automate and optimize a design for power, performance and area (cost).

Manufacturing

Semiconductor manufacturing consists of two sets of processes: front-end wafer fabrication; and back-end packaging, assembly, and testing. Sophisticated equipment and materials support both sets of processes. As manufacturing processes improve, designers have greater scope to design better chips.

Front-End Wafer Fabrication. Highly specialized semiconductor manufacturing facilities, known as "fabs," apply chip designs to silicon wafers. Each wafer usually contains multiple chips of the same design. The fabrication process is intricate and requires highly specialized inputs and equipment. Depending on the type of product, the process will consist of between 400 and 1,400 steps and may take 14 to 20 weeks to complete.

Design and front-end wafer fabrication are closely linked. During the design process, initial work is done on an electronic, software-based model of the chip. Fabs then provide test silicon to validate the electronic model and provide vital input on the design's manufacturability. Close collaboration is critical: scaling up new processes involves inherent uncertainties in modeling and reaching target manufacturing yields. Design engineers and wafer fabrication engineers use PDKs—essentially documentation of fabrication processes—and work together to debug design features and verify that manufacturing processes and chip designs are compatible.

Back-End Packaging, Assembly, and Testing. Semiconductor assembly companies convert silicon wafers into finished chips to be assembled into electronic devices. Silicon wafers are sliced into individual chips, packaged, rigorously tested, and then shipped to electronic device manufacturers.

Equipment and Materials

Semiconductor manufacturing uses more than 50 types of sophisticated equipment for front-end and back-end processes. Lithography tools, which are critical for producing advanced chips, represent one of the largest capital expenditures for fabrication players. Semiconductor manufacturing also uses as many as 300 specialized materials.

Types of Semiconductor Design Activities

There are two major types of semiconductor design activity:

- **Hardware Design.** Semiconductor hardware goes through a multistep design process that involves production definition and specification, system design, integrated circuit design, and post-silicon validation. These steps were illustrated in Exhibit 3 of the main text.

- **Software Development.** Software development involves the creation of firmware, a type of software that is embedded on hardware to provide low-level control over specific functions such as operating a camera. Firmware can enable higher-level software such as an operating system, it can interact with and control a specific device, or it can work as a standalone if the device is sufficiently simple. Software development may also involve the creation of platforms and software development kits (SDKs) that other companies can use to build complex functionality such as AI vision systems.

Semiconductor Design Workforce and Market Share Model

The semiconductor design workforce and market share model analyzes semiconductor design workforces in various regions of the globe: Europe, India, Japan, mainland China, South Korea, Taiwan, the US, and the rest of the world. The model also analyzes the current US-based semiconductor design workforce, along with trends that will impact its size in the coming years, to project the size and skills of the US semiconductor design workforce in 2030. This model supports the projections identified in Exhibits 5 and 11 of the main text of this report.

The model evaluates current and projected trends in the productivity of semiconductor design workers, considering their skills, employers, regions of residency, and other factors. The model also considers revenue growth rates for the global semiconductor industry, and it integrates this information to project the revenue market shares of each region in 2030.

For the US-based workforce, inflow trends that the model considered include new graduates in semiconductor-related fields, rates of entry into semiconductor industry, and immigration. The outflow trends that it considered include retirements, exits from the industry, and voluntary and involuntary emigration. The model also takes into account the different skills needed in semiconductor design, including but not limited to education levels (for example, PhD degree holders versus bachelor's degree holders) and subdomains of expertise (for example, software specialists versus hardware specialists).

In addition to forecasting on the basis of existing status quo trajectories, the model uses scenarios to assess the impact of changes in individual variables on supply of and demand for US-based semiconductor design engineers in 2030.

For additional information, please contact the authors.

Return on Public Investment in Semiconductor R&D Model

The return on public investment in semiconductor R&D model analyzes impacts of public investment on the US economy under various scenarios. This model supports the report's estimates of returns on public dollars invested.

The model analyzes the growth of global and US semiconductor industry revenues through 2030 on the basis of industry forecasts and financial data. It examines the composition of the US semiconductor industry, the share of design activity that occurs in the US, and the expected level of investment in design and R&D, combining this information with findings from academic studies on the direct, indirect, and induced impacts of new R&D investment on GDP and jobs. The model then integrates with analyses in the semiconductor design workforce model to consider changes in the size and skills of the US design workforce over time and the impact of workforce changes on the return on public investment.

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