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SEMICONDUCTOR
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EMERGING RESILIENCE IN THE SEMICONDUCTOR SUPPLY CHAIN

MAY 2024

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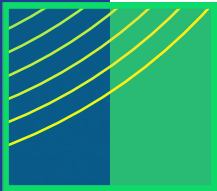
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Executive Summary

There are strengths and vulnerabilities in the global semiconductor supply chain.

Our April 2021 report¹ illustrated that the globally integrated nature of the semiconductor supply chain has realized \$45 billion–\$125 billion in cost efficiencies each year, contributing to prices 35%–65% lower than they would otherwise be with fully localized supply chains, resulting in enhanced adoption of downstream products and services. But we also showed that the industry has become vulnerable to geographic concentration—with at least 50 points across the supply chain where one region held over 65% of global market share. Disruptions, such as pandemics, natural disasters, materials shortages, or conflicts, could substantially impact the global chip supply chain.

Governments and companies are taking concerted action to increase resilience. The US CHIPS Act, signed into law in August 2022, committed \$39 billion in grant incentives and a 25% investment tax credit (ITC) for semiconductor manufacturing.

The European Union (EU) unveiled the European Chips Act, Mainland China initiated the third phase of its Integrated Circuit (IC) Industry Investment Fund, and various other incentive programs emerged or expanded in Taiwan, South Korea, Japan, India, and other countries. In parallel, companies have made significant investments, in both established and new regions. We project around \$2.3 trillion in private sector investment in wafer fabrication in 2024–2032, compared with \$720 billion in the 10 years prior to enactment of the CHIPS Act (2013–2022). The US is projected to capture 28% of these capital expenditures, as opposed to the pre-CHIPS Act pace of investment, in which the US would have captured just 9% of global capital expenditures.

Wafer fabrication will become more resilient. By 2032, we predict leading-edge wafer fabrication capacity to diversify beyond Taiwan and South Korea to include the US, Europe, and Japan. We expect the US to increase its fab capacity by 203% between 2022 and 2032, the largest increase in the world. As a result, the United States will reverse a decades-long downward trajectory and raise its share of global aggregate fab capacity from 10% today to 14% in 2032. In the absence of action, the US share would have slipped further to 8% by 2032.

New markets and innovative technology can support resilience in assembly, test, and packaging (ATP).

In ATP, Mainland China and Taiwan will continue to hold the largest share of global capacity. But with support from governments and foreign investors, we expect countries in Southeast Asia, Latin America, and Eastern Europe to expand ATP activity. The US State Department is supporting these efforts through International Technology Security and Innovation (ITSI) funding under the CHIPS Act. Emerging market governments are actively pursuing their own strategies to attract ATP investment. In parallel, the development of advanced packaging—and associated innovations in chiplets—is also driving leading players to build ATP capacity in the United States and Europe, proximate to new wafer fabrication capacity.



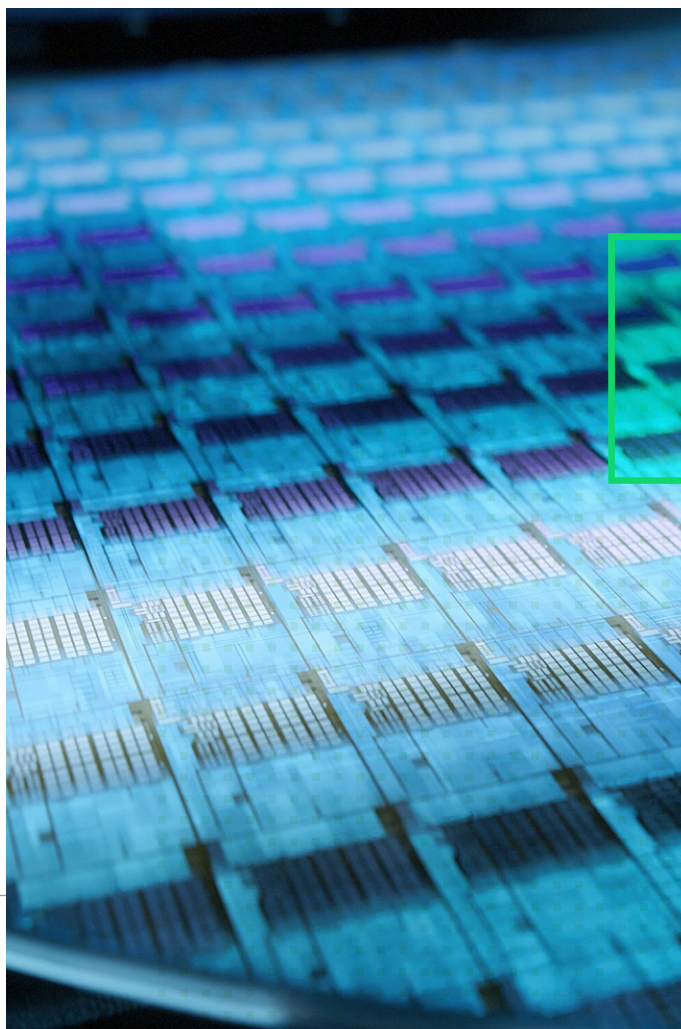
Other parts of the supply chain are also achieving a better balance. In design, core IP, and Electronic Design Automation (EDA), companies are diversifying where they hire, locate, and train talent. In semiconductor manufacturing equipment (“tools”), current industry leaders are establishing R&D and training centers in different regions. Although materials production remains concentrated in East Asia, we expect it to follow future fab capacity to the United States and Europe to realize cost and R&D benefits.

A strong global talent pipeline is as important as ever. As semiconductor companies pursue ambitious development plans in the context of a tight labor market, they rely on access to engineers and technicians to fill both high- and mid-skill positions. Improving workforce development across established and emerging regions, while also advancing immigration policies to foster global talent flows, will be vital to the semiconductor industry’s future resilience.

Scale and openness are critical for resilience. To ensure new and diversified semiconductor facilities can operate at optimal capacity utilization rates to generate a positive return on investment, it is vital for chip companies to maintain continued access to global customers and a global network of suppliers. Governments are increasingly imposing constraints on where chip companies can sell their products and services, or where they can source inputs and equipment. Fortunately, global trade in semiconductors continues to grow at a rapid pace, reflecting the global interconnectedness of the industry. The United States and allied governments need to maintain open trade and cooperation by recognizing that extreme industrial policies, such as full country-level “self-sufficiency,” will undermine resilience, add cost, and stifle innovation.

Industrial policies have the potential to create additional bottlenecks that increase supply chain risk. Certain segments of the semiconductor supply chain are at risk if incentive programs and large-scale industrial policies lead to non-market-based investment, which can result in overconcentration or oversupply. Government incentives should focus on enabling targeted, distributed, market-based investments.

Sustained support for resilience is needed. Over the coming decade, the semiconductor supply chain will continue to face challenges, including industry cyclicality and the rapid evolution of downstream demand (for example, in AI, EVs, industrial automation, and robotics). Supply-demand imbalances in mature node capacity could become more evident. It will be critical for policymakers in the United States and elsewhere to “stay the course” by extending current support as well as considering additional measures to strengthen resilience.



Introduction

Semiconductors power today's economy, from vehicles and mobile devices to data centers, medical equipment, clean technologies, and, of course, the upcoming AI revolution. The invention of the integrated circuit (IC) started the United States on a path to early leadership in design and manufacturing. Beginning in the 1980s, chip manufacturing rapidly shifted from North America to Japan and East Asia. While the United States remained preeminent in equipment and chip *design*, East Asian economies increased their share of *wafer fabrication capacity*, highlighted by the rise of South Korea in memory and Taiwan in the pure-play foundry business for all other semiconductors. This configuration enabled rapid advances and specialization, but over time, led to supply chain concentration.²

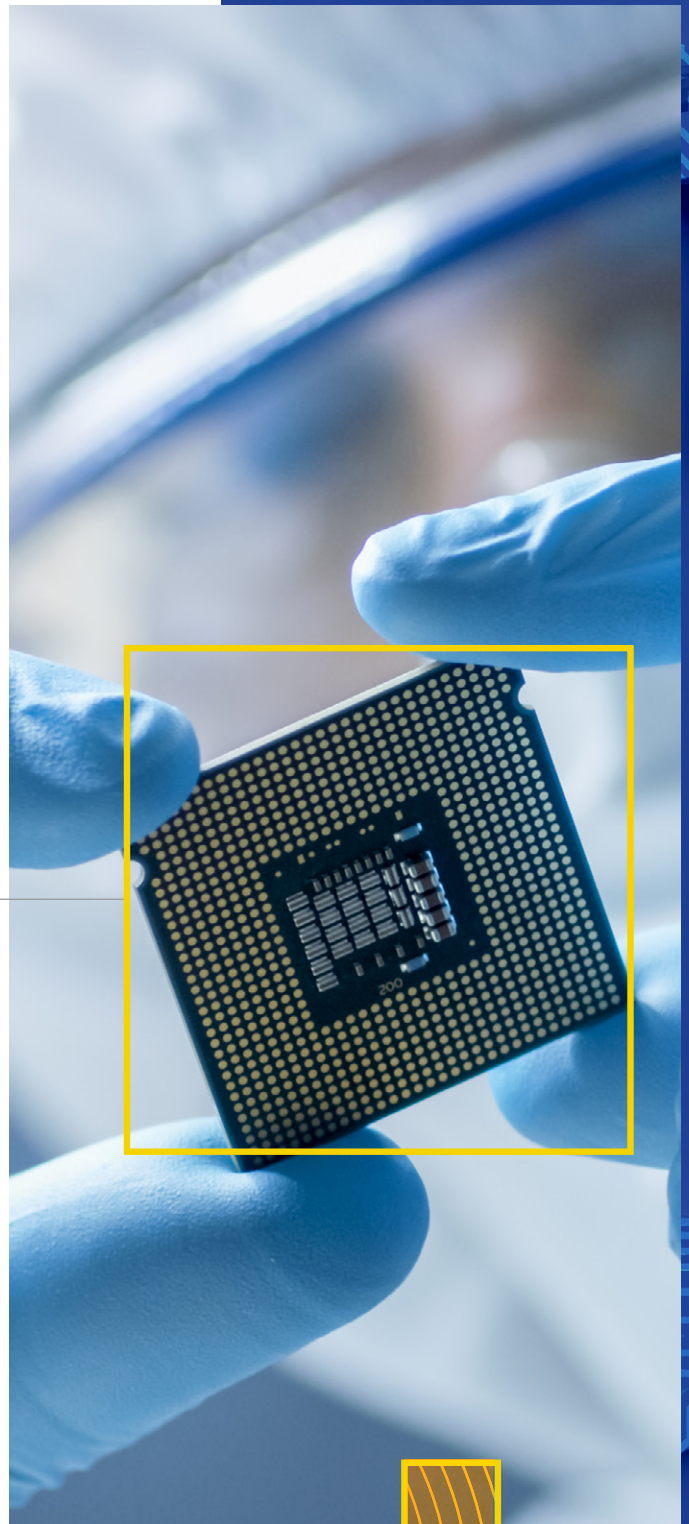
In *Strengthening the Global Semiconductor Supply Chain in an Uncertain Era* (April 2021), we analyzed the semiconductor supply chain to understand its value for the global economy, while also identifying points of vulnerability. We recommended policies and other actions to improve supply chain resilience through greater geographic diversification.

Since then, the global supply chain has evolved rapidly, with major private sector investments in multiple geographies and public sector policies and support programs directed at the industry.

The US CHIPS Act, signed into law in August 2022, committed \$39 billion in grants and loans for semiconductor manufacturing. Likewise, the European Union unveiled the European CHIPS Act, Mainland China initiated the third vintage of its IC Industry Investment Fund, and various other incentive programs emerged across Asia and other regions. In parallel, over 100 new semiconductor manufacturing investments have been announced to meet increased market demand, dispersed worldwide across every major region.

In this report, we provide an updated view on the impact of policies today on future investment in the global semiconductor supply chain and the implications for resilience. We define resilience, broadly speaking, as improved *geographic diversification* of the supply chain. We begin by reviewing public and private sector strategies across major geographies, with additional detail provided in the **Appendix**. We then assess the likely effects of these trends over the coming decade, specifically forecasting changes in distribution of wafer fabrication and ATP capacity. We also consider geographic diversification in other segments of the supply chain,³ including design, core IP, and EDA, equipment, and materials.

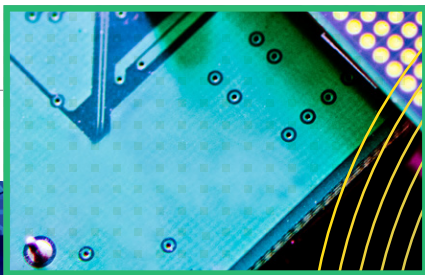
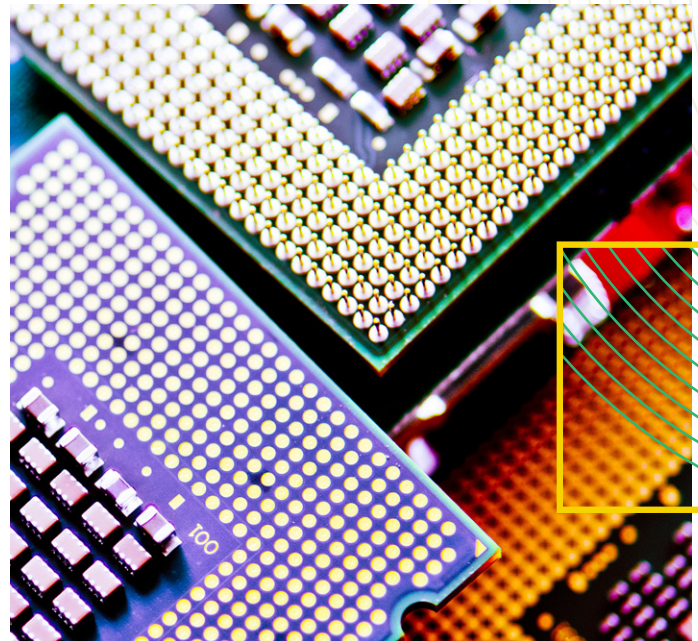
Our report then highlights the path toward greater resilience, including sustaining government support, guarding against supply-demand imbalances, integrating new countries, maintaining vibrant global trade, and fostering global talent. As geopolitical frictions persist, it is important to maintain a global supply chain and support a more diverse global production footprint. Accordingly, we close our report by highlighting future needs of the industry.



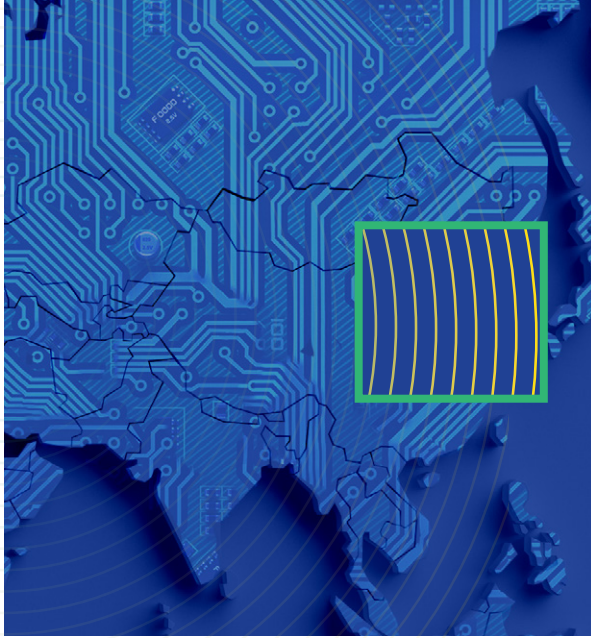
The Expansion of Government Incentives

Semiconductor companies weigh many factors when making investment decisions, including overall business conditions, supplier networks, site availability, infrastructure, and workforce—but a significant overarching factor is government policy. Well-crafted and durable incentive programs, along with an enabling regulatory environment and effective talent development initiatives, also signal a government’s commitment to the industry’s long-term success. For individual companies, effective policies can improve the cost and efficiency of constructing and operating a facility.

Since our report in April 2021, governments around the world have made substantial efforts to increase their support for the semiconductor industry (see **Exhibit 1**; for more information on incentive programs in each key region, see the **Appendix**).



The United States passed the CHIPS Act to incentivize growth of the semiconductor ecosystem through both direct grants and a 25% ITC for semiconductor manufacturing, and several states have enacted incentive programs to supplement the federal efforts. \$11 billion of the \$52 billion appropriated in the CHIPS Act is to be used to develop US leadership in semiconductor R&D, emphasizing the importance of an all-encompassing industrial policy to success. In the EU and Japan, governments have appropriated large grant funds to be allocated on a national and project-specific basis, coupled with tax incentives. The South Korean and Taiwanese governments are offering comparatively larger tax incentive programs and R&D support—for example, in the Taiwan Chip Innovation Program and South Korea’s K-CHIPS Act. These direct incentives are complemented by indirect tools to attract investment, such as infrastructure support, low-cost access to land, and streamlining government approvals.



Mainland China’s large and wide-ranging support for the semiconductor industry also will impact the global supply chain in the coming years. A large portion of Mainland China’s support has come in the form of equity infusions and the operation of funds that mix government and private capital. Other factors, such as overseas talent acquisition, the formulation of domestic standards, state ownership, and the preference given to domestically produced chips, further act to support Mainland China’s semiconductor industry.

EXHIBIT 1

Government incentives by major region (left to right by size of GDP)

	US	Mainland China	EU	Japan	South Korea	Taiwan	
Guidance	Target	Achieve resiliency in semiconductor supply chain	Reach 70% self-sufficiency by 2025	Gain 20% global share by 2030	Earn \$112B sales by 2030	Secure foothold in Logic, bolster fab leadership	Breakthrough 1 nm by 2030
	Guiding policy	CHIPS and Science Act, 100-Day Supply Chain Review	National IC Outline, 14th Five Year Plan	Digital Compass 2030	Strategy for Semis and the Digital Industry	K-Belt Semiconductor Strategy	Angstrom Semiconductor Initiative, Moonshot program
Measures	Key Incentive amounts	\$39B in grants ¹	\$142B in equity funds	\$47B in grants	\$17.5B in grants	\$55B in tax incentives	\$16B in tax incentives ⁴
	Key Initiatives	25% investment tax credit Grants under the CHIPS Act State-level support	Big Fund I, II, III and local funds State-owned enterprise leaders National science fund	Grants and loans under EU Chips Act Tax credits State aid allowances ²	National fiscal funding Leading-Edge Semiconductor Technology Center	Tax incentives under K-Chips Act Private-public education programs	Financial subsidies under the Chip Innovation Program Industry-academia co-op, tax credits
Impact	New fab & ATP investments since 2020³	26	~30 ⁵	8	4	3	7

1. \$39B for manufacturing; \$13.2B for R&D and workforce development
 2. Important Projects of Common European Interest (IPCEI)
 3. Comprises fab and ATP projects that have been announced, started, or completed since 2020
 4. 25% tax credit pledging to give back \$2.25B per annum over 7 years.
 5. May undercount the total number of sites in China.
 Source: Gartner; SIA; Press releases; Company disclosures; Government websites; BCG analysis

Resilience in the Semiconductor Supply Chain

The global semiconductor supply chain is highly specialized (see Exhibit 2). Different regions have strengths in different areas. For example, US-headquartered companies lead in design, core IP, and EDA; the United States, EU, and Japan jointly lead in equipment; companies headquartered in Mainland China, Japan, Taiwan, and South Korea lead in materials; South Korea- and Taiwan-headquartered companies lead the world in advanced node fabrication (sub-10 nanometer chips); and ATP footprint is concentrated in Mainland China and Taiwan.

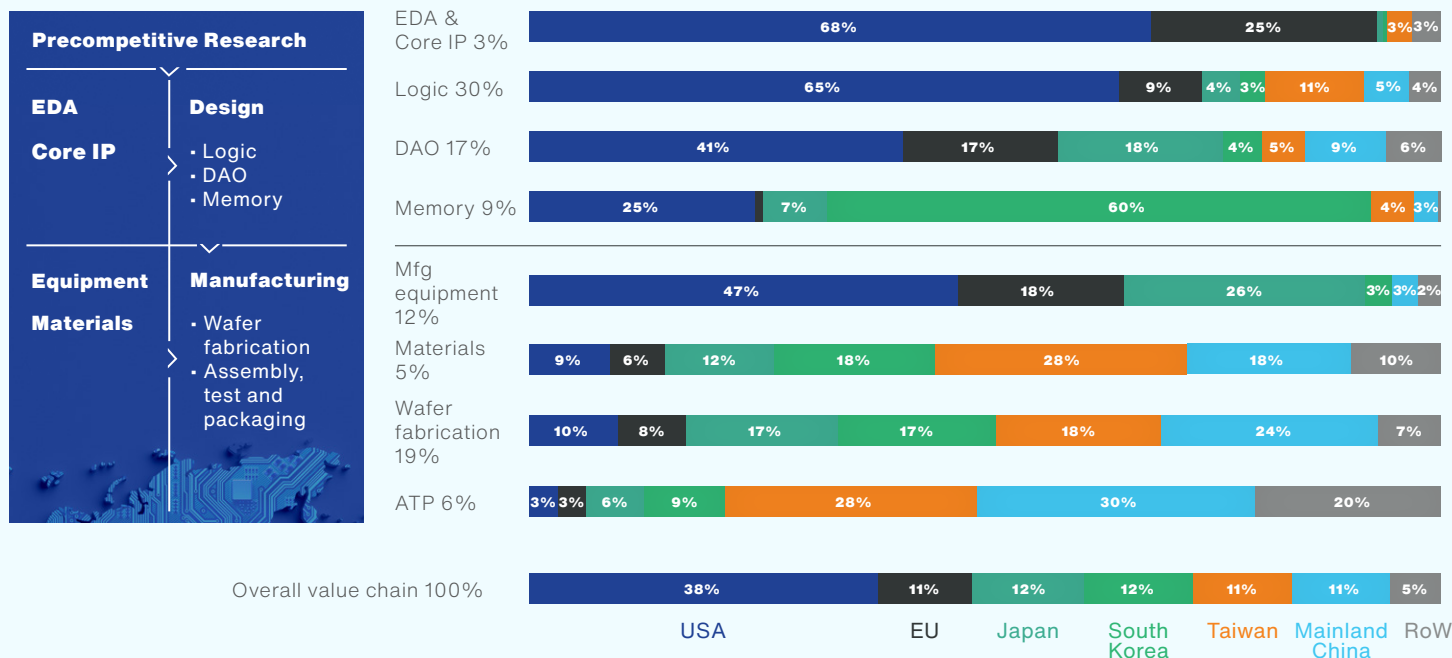
Specialization by region has been enabled by the globally integrated nature of the supply chain, which has allowed each specialized company to access the global market. But it has also created vulnerabilities in terms of geographic concentration. Looking ahead, we expect significant geographic

diversification, mainly in two areas to start with: (i) wafer fabrication, particularly in advanced logic and (ii) ATP, with a diversification of activities outside Mainland China and Taiwan to include substantial gains for new markets. It is unlikely that ATP will locate in the United States, due to cost pressures, the exception being certain advanced packaging facilities near new fab sites. To a lesser extent, we also expect greater diversification in design, as market leaders source talent globally, and materials, as vendors follow new fab capacity to different regions (see Exhibit 3). In equipment as well as EDA and core IP, meaningful diversification will prove challenging given the high degree of specialization and vendor concentration today, as well as the lesser necessity of co-locating with fab sites.

Below we discuss these trends in depth for each segment of the supply chain.

EXHIBIT 2

Semiconductor industry value-added by activity and region, 2022 (%)

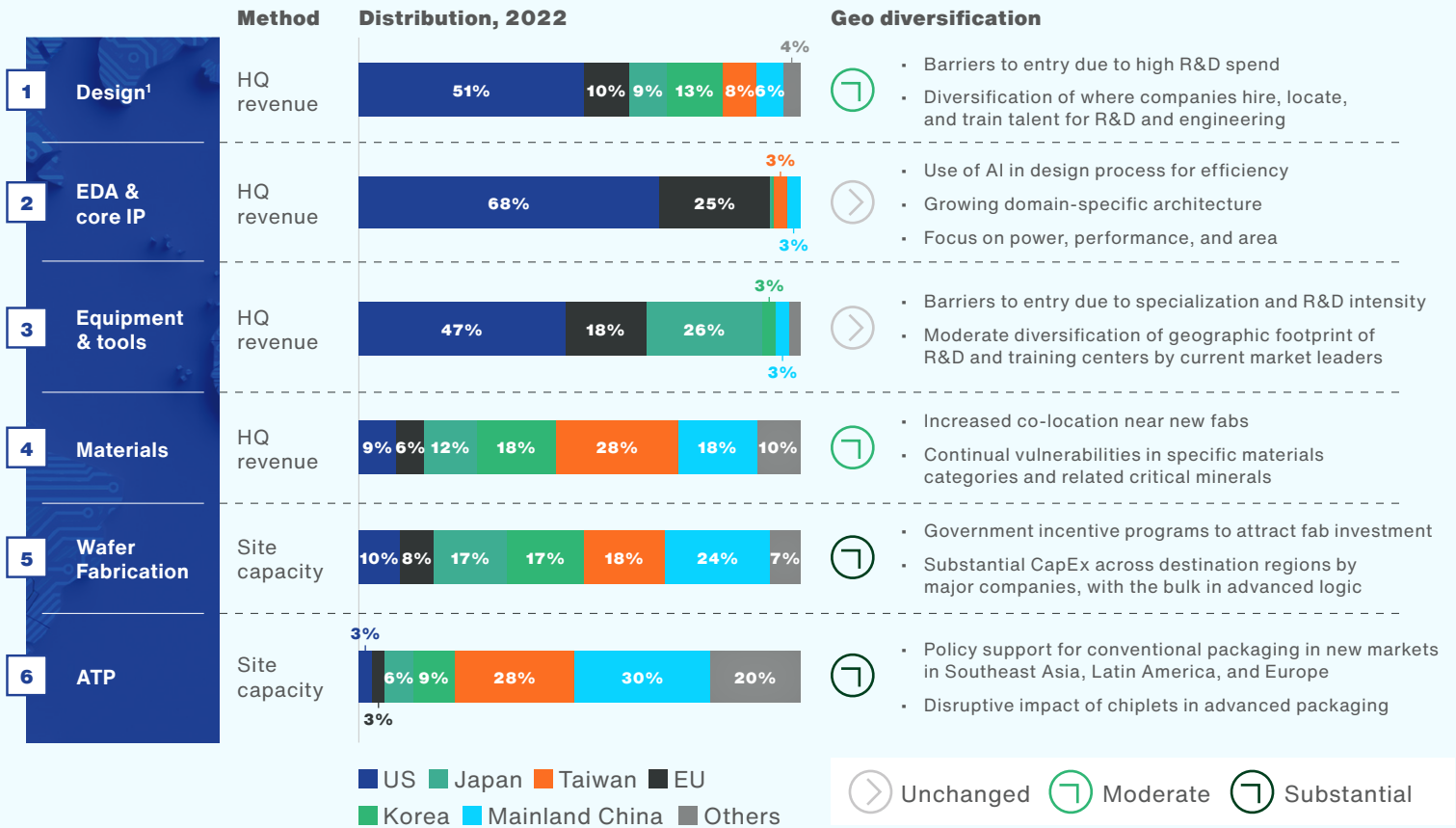


Notes on regional breakdown: EDA, design, manufacturing equipment, and raw materials based on company revenues and company headquarters location. Wafer fabrication and Assembly & testing based on installed capacity and geographic location of the facilities.

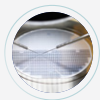
1. Includes Israel, Singapore, and the rest of the world

Source: IPnest; Wolfe Research; Gartner; SEMI; BCG analysis

Diversification by Supply Chain Segment



1. Represents both fabless and IDM design
 Source: SEMI; Yole Group; BCG Analysis



Wafer Fabrication

We begin with wafer fabrication, which exerts a “pull” effect on investment in other segments of the supply chain. Given the capital requirements and substantial lead time to bring projects online (upwards of five years in some cases), wafer fabrication is where government and industry efforts have focused substantially to date.

We project around \$2.3 trillion in private sector investment in wafer fabrication in 2024–2032, compared with \$720 billion in the 10 years prior to enactment of the CHIPS Act (2013–2022). The over 100 major semiconductor manufacturing ecosystem projects that have been announced since our prior report are spread out—both around the globe and to new locations within each major region (see Exhibit 4).

Asia:

Investments continue at pace across the region. Local companies in Taiwan have announced plans to stand up seven new fabs on the island itself. TSMC is also partnering with Sony, DENSO, and Toyota to boost manufacturing capabilities in Kumamoto, Japan, and Japanese officials are helping domestic startup Rapidus set up production lines for cutting-edge 2 nanometer chips at a new site in Hokkaido. South Korea has announced a plan to invest \$471 billion through 2047 to build 16 new fabs in a mega chip cluster in Gyeonggi Province, involving Samsung, SK Hynix, and other chip companies.⁴ In Mainland China, domestic Chinese companies are making new investments in fabs in Shenzhen, Tianjin, and Shanghai.

United States:

Between 2020 and year-end 2023, 80 new semiconductor manufacturing projects were announced across the United States alone, projected to create 50,000 direct new jobs.⁵ A portion of these investments is going to areas with a mature semiconductor footprint, such as Texas, Arizona, New York, and California. But there have also been substantial investments in Greenfields and capacity expansions in newer regions, such as New Albany, Ohio.



Europe:

There has been substantial investment in new capacity in Europe, with seven major wafer fab investments announced since 2020. The lion's share of this capacity is being built in eastern Germany, including Intel's investment in Magdeburg and TSMC's joint investment with leading European semiconductor manufacturers to construct a new facility in Dresden. Still, the momentum is not limited to Germany; in the south of France, GlobalFoundries has partnered with STMicroelectronics to build a \$3.1 billion fab in Crolles, and Poland is poised to host a new Intel advanced packaging facility.

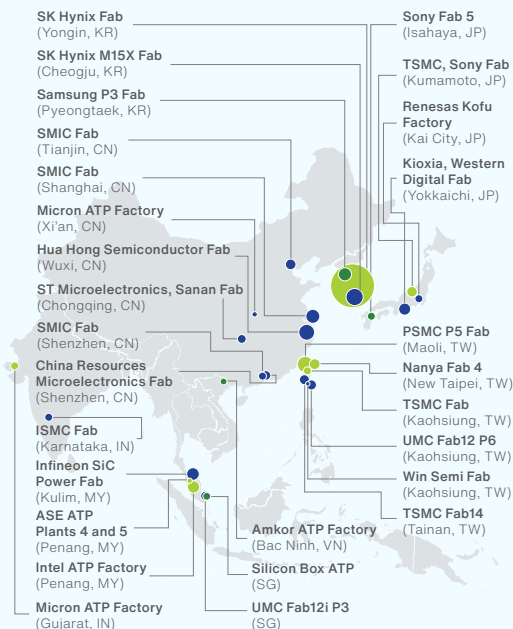
In consequence, we expect significant investment to flow between regions between now and 2032 (see Exhibit 5).

Between 2020 and year-end 2023, 80 new semiconductor manufacturing projects were announced across the United States alone

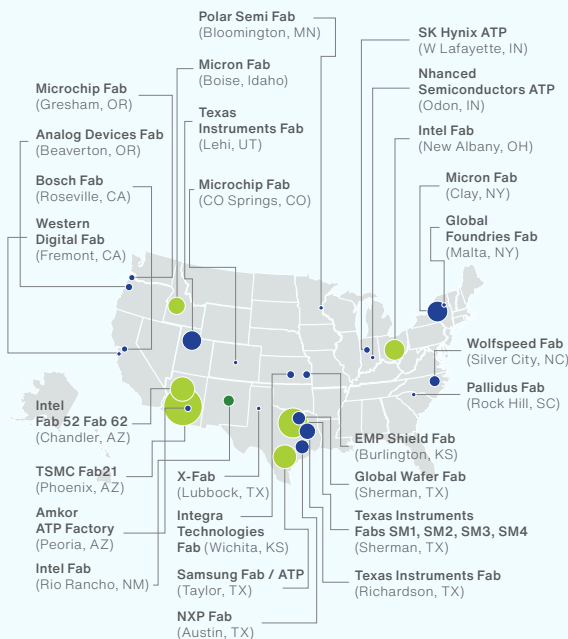
EXHIBIT 4

Major new fab and ATP investments announced across the world since 2020

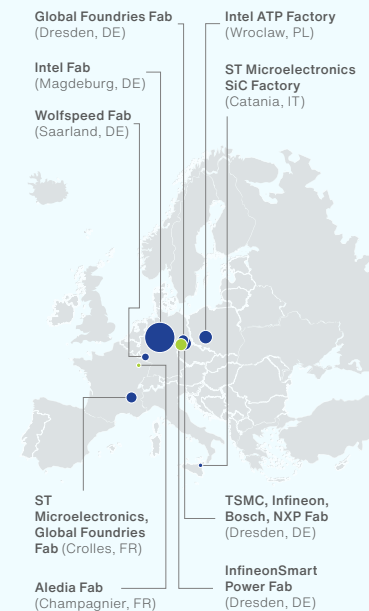
ASIA



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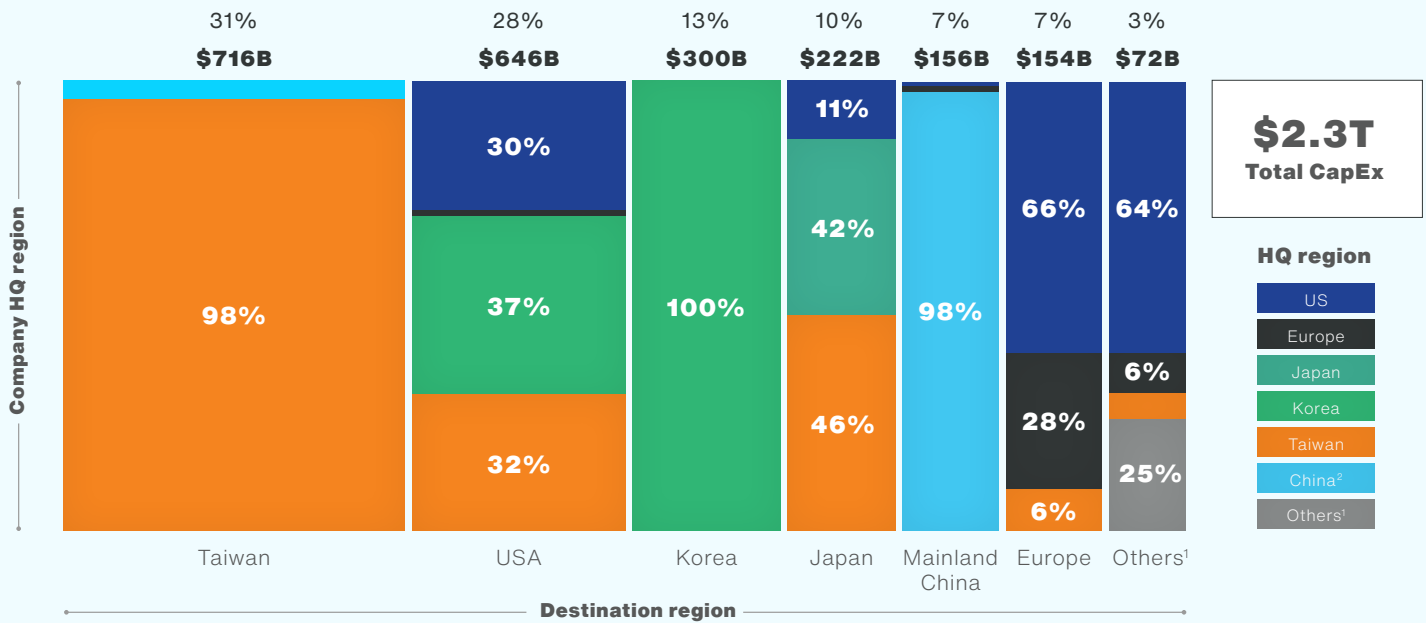
EUROPE



■ Planned ■ Started ■ Completed © Investment size (\$) • \$2B

Note: Includes investments over \$100M from 2020 onwards in Fabs and ATP facilities.
Source: Gartner; SIA; press releases; company disclosures; BCG analysis

Future flows of CapEx⁶ from company HQ region to destination region, 2024-2032F

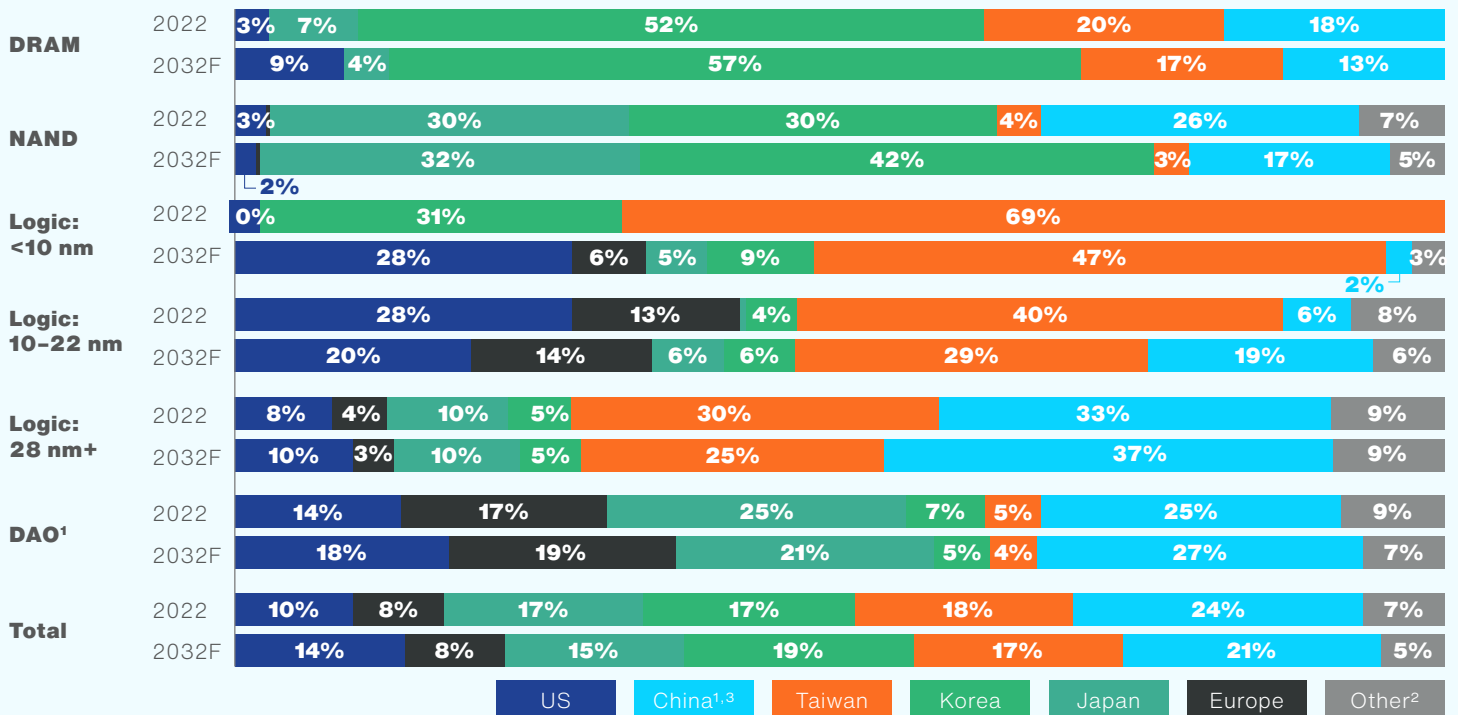


1. Others includes Israel, Malaysia, Singapore, India and the rest of the world
 2. Mainland China
 Source: SEMI; BCG Analysis

Advanced logic currently comprises processes newer than 10 nanometers. We expect the definition of “leading-edge” capacity to comprise processes newer than 3 nanometers by 2030.⁷ Advanced logic will attract a larger share of investment, driven by data centers, networking equipment, PCs, smartphones, smart “edge” devices with machine learning and artificial intelligence (ML/AI) capabilities, and automotive advanced driver-assistance systems (ADASs), among other applications.⁸ Indeed, nearly 70% of CapEx will go toward chips manufactured on sub-10 nanometer technologies, because they are substantially more expensive to produce. This trend implies tradeoffs. Investing heavily in the leading edge can allow a region to compete at the forefront of innovation but will not be fully reflected in terms of wafer starts per month; investing in legacy processes, on the other hand, allows a region to realize more near-term value for money and employment, at the risk of creating excess capacity for segments where demand may be fixed or waning.

The investment pattern for advanced logic has become more distributed around the globe, with Taiwanese and South Korean companies investing significantly more in the United States, Europe, and Japan. Advanced logic⁷ capacity will see a shift—from almost 100% distributed between South Korea and Taiwan in 2022 to more than 40% being outside these regions by 2032. In 2022, the United States did not produce any advanced logic chips. By 2032, the United States will produce nearly 30% of all logic chips at processes newer than 10 nanometers. In addition, when the projected fabs come online, Europe and Japan will host a meaningful ~12% of chips newer than 10 nanometers as well (see Exhibit 6).



Global wafer fabrication capacity⁹ by technology category by region, 2022 (top) and 2032 Forecast (bottom) (%)

1. Discretes, analog, and optoelectronics & sensors; 2. Others includes Malaysia, Singapore, India, and the rest of the world; 3. Mainland China

Note 1: Looked at fabs with over 5K+ wspm and 8+ inch wafer size; excluded R&D fabs.

Note 2: May not total 100% due to rounding.

Source: Department of Commerce; SEMI; BCG Analysis

For logic processes in the range of 10 to 22 nanometers, Japan will develop a meaningful 5% presence from a standing start, and Mainland China will triple its share from 6% to 19%. Logic at or older than 28 nanometers is poised to remain well distributed—with multiple regions in the game and most regions experiencing small share moves. Mainland China shows the biggest share gain, going from 33% share in 2022 to 37% in 2032.

In other process technologies, dynamic random-access memory (DRAM) will remain highly concentrated in South Korea, but with the United States increasing its share threefold from 3% to 9%. Geographic concentration will increase in NAND memory—with South Korea moving from 30% to 42% share, and Japan and South Korea combined accounting for ~75% of capacity by 2032. Finally, discrete, analog, and optoelectronics chips (DAO) will stay well distributed, with all major regions participating at 5% share or greater.

The net result of these specific, strategic, and targeted moves by companies is to improve resilience of the industry on a more “average” global capacity share by region (see Exhibit 7). The United States is set to increase its share of global capacity from 10% to 14%. Without the CHIPS Act, the United States

would have seen its share decline to 8% of global capacity by 2032. This corresponds to our projection that the US will capture 28% of global capital expenditures, as opposed to the pre-CHIPS Act pace of investment, in which the US would have captured just 9% of global capital expenditures.

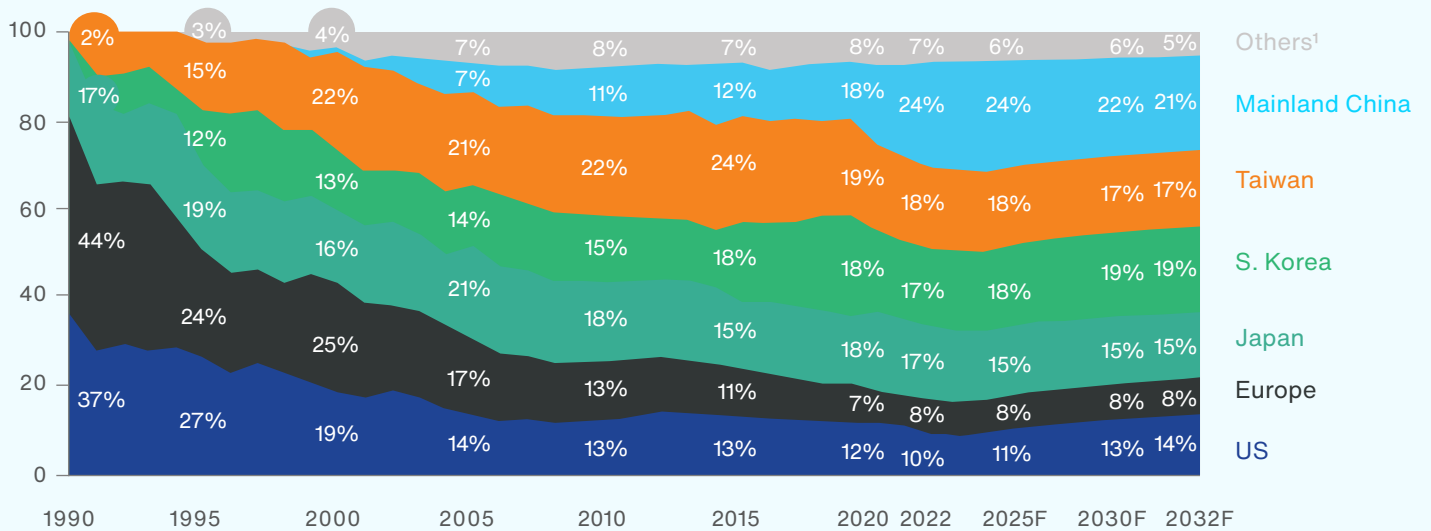
Moreover, we expect each major region to grow its capacity by over 80% over the next decade.

The United States, at 203%, will grow capacity at a faster rate than other regions

The United States, at 203%, will grow capacity at a faster rate than other regions and much faster than in the preceding decade (see Exhibit 8). In terms of thousands of wafer starts per month (300 mm equivalents), this represents an increase from 1,121 kwsmp (thousands of wafer starts per month) in 2022 to 3,393 kwsmp (203% increase) in 2032.

EXHIBIT 7

Global 200mm+ commercial semiconductor fab capacity share by region, 1990-2032F



1. Others includes Malaysia, Singapore, India, and the rest of the world

Note 1: Rounding errors. All values shown in 300 mm (12") equivalents; excludes capacity below 5K wspm or produced on wafer sizes less than 8"

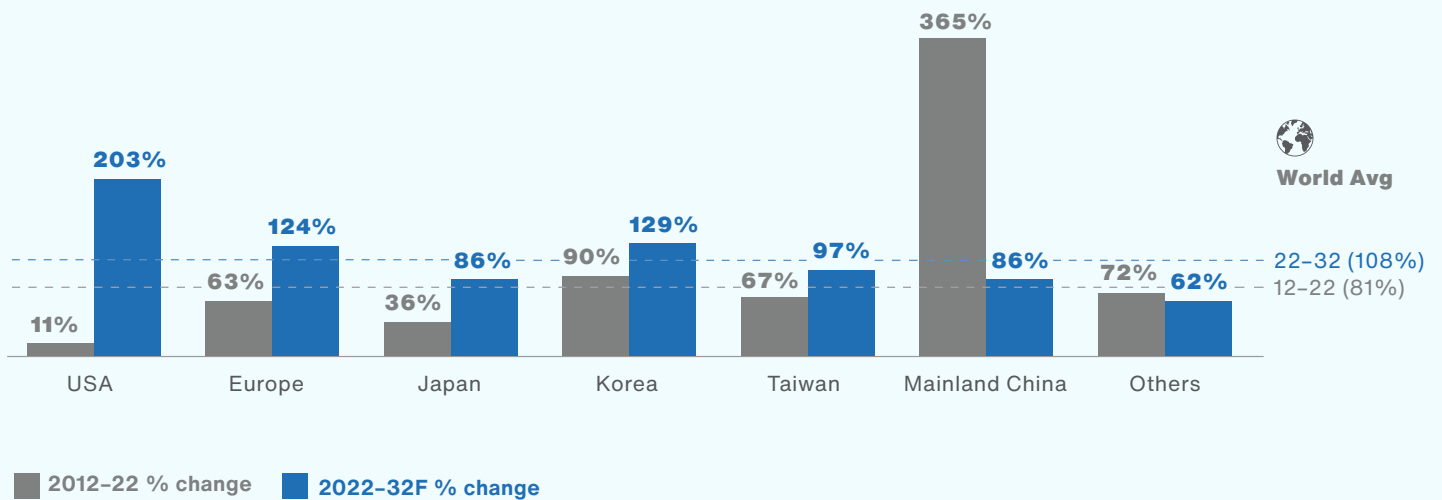
Note 2: May not total 100% due to rounding.

Source: SEMI; BCG analysis

EXHIBIT 8

Semiconductor capacity increase by region, 2022-2032F

(% change in wspm capacity)



Source: SEMI; BCG analysis



Design, Core IP, and EDA

Design, core IP, and EDA are R&D-intensive, non-manufacturing segments of the supply chain. Across all design activities (fabless and IDM), US-headquartered companies hold 51% of the design market. The United States is also home to the leading players in EDA software, and the UK and US are home to the leaders in IP.

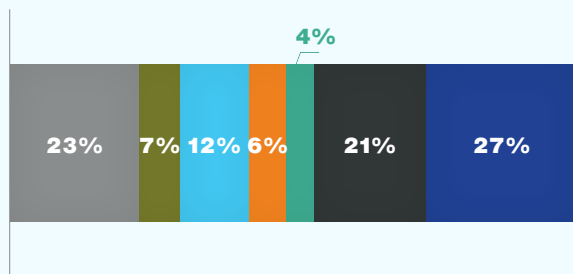
Nonetheless, in these talent-driven parts of the supply chain, companies are diversifying where they hire, locate, and train talent for R&D and engineering. According to a 2023 survey undertaken by the US Department of Commerce Bureau of Industry and Security (BIS), surveyed companies cited Europe, Mainland China, and India as the leading non-US locations for their design activity.¹⁰ A November 2022 BCG-SIA report on semiconductor design also found that design activities are distributed around the globe. Mainland China and India are the locations with the most semiconductor design engineers outside the United States (see Exhibit 9).¹¹



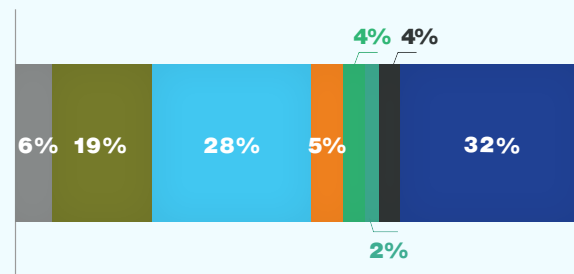
EXHIBIT 9

Left: Design facilities, by location (% of facilities of design companies by location);
Right: Design engineers by location (% of design engineers by location)

Design activity by location¹
 % of facilities in each location



Design engineers by location²
 % of engineers in each location



■ US
 ■ Japan
 ■ Taiwan
 ■ South Korea
 ■ Europe
 ■ India
 ■ Mainland China
 ■ All Others

Note 1: left chart based on Bureau of Industry and Security (BIS) survey (December 2023) of companies involved in semiconductor design (fabless and IDM)

Note 2: right chart based on BCG-SIA analysis of LinkedIn profiles of engineers associated with semiconductor design (fabless only); excludes engineers associated with manufacturing R&D; previously referenced in BCG-SIA Design report ("The Growing Challenge of Semiconductor Design Leadership," November 2022)

Source: Commerce-BIS; LinkedIn; BCG analysis

There are now over 3,000 fabless design companies in Mainland China, with double-digit annual revenue growth



In design, there is a growing need for specialty chips, such as AI accelerators, to accommodate the proliferation of new devices and associated functions.¹² Meeting this demand opens the door to new vendors in different regions, including new markets—India, for example, is home to an estimated 20% of all design engineers.¹³

Mainland China's state support for design and EDA activities could also reshape industry segments and challenge US design and EDA leadership. The National IC Funds I and II allocated funding worth billions of US dollars toward fabless design companies, and National IC Fund III is poised to do the same. There are now over 3,000 fabless design companies in Mainland China, with double-digit annual revenue growth.¹⁴ Mainland China's indigenous chip designs have focused on consumer electronics, industrial control systems, and intelligent device chips, but are less competitive in advanced CPUs, GPUs, and FPGAs and corresponding high-end servers and computer power management.¹⁵ Nonetheless, Mainland China's fabless design segment is likely to consolidate and achieve advances in the coming decade. Various manufacturers in Mainland China are starting to establish fabless design units capable of designing their own chips—for example, Xiaomi, a leading mobile device, home device, and EV producer.¹⁶ Moreover, National IC Fund allocations have focused in particular on GPU and FPGA, and support some of Mainland China's major national semiconductor projects.¹⁷ US leadership in EDA should not be taken for granted. Between 2018 and 2023, Emyrean Technology, Mainland China's leading entrant in EDA software, realized a sixfold increase in revenues. (Emyrean predominately sells into the Mainland China market, but could soon grow its international sales.¹⁸)

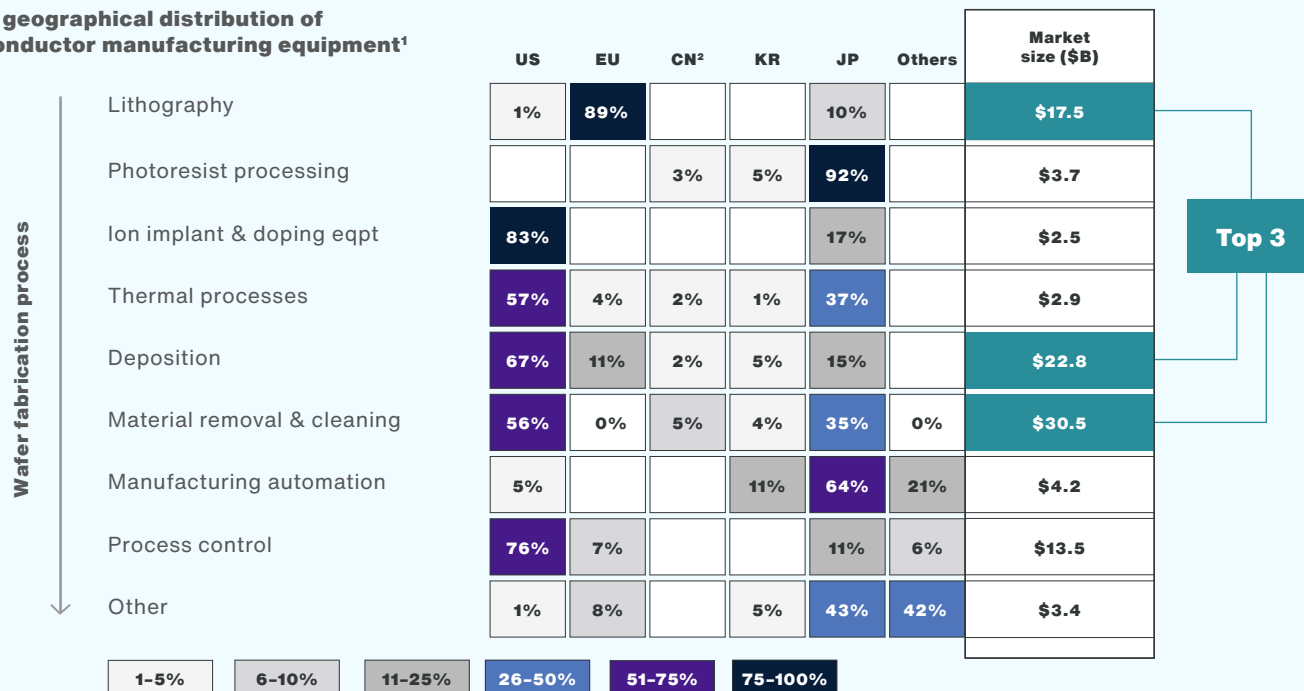


Equipment & Tools

The \$110 billion semiconductor equipment market spans more than 50 types of specialized equipment, but concentration is significant in some areas. Three segments—lithography, deposition, and materials removal & cleaning—comprise 70% of the market, each dominated by a handful of key vendors. One European company makes up 87% of the lithography market. In deposition as well as materials removal and cleaning, three companies—two based in the United States and one based in Japan—comprise 70%–80% of the market (**see Exhibit 10**).

Semiconductor manufacturing equipment vendors, by HQ region revenue

Global geographical distribution of semiconductor manufacturing equipment¹



1. Geographies based on company HQ's; distribution based on company revenues 2. Mainland China Source: Gartner; BCG analysis

Although R&D intensity creates barriers to new entrants, current market leaders are diversifying the geographic footprint of their R&D and training centers, which will add to resilience. The top 15 equipment vendors have manufacturing facilities in a total of 17 countries. These also include new training centers to increase the pool of talent outside their home regions. For example, ASML opened a training center in Taiwan for operating EUV lithography equipment, in support of TSMC. LAM Research has opened a new R&D facility in South Korea for semiconductor equipment and process technology to enable faster and closer engagement with customers. KLA is building an R&D and manufacturing center in Wales in the UK.

Moreover, Mainland China's efforts to build capacity and ultimately achieve self-sufficiency in equipment are notable. Mainland China currently accounts for 20% of global equipment spend and 18% of global equipment imports. Export controls by the United States, Japan, and the Netherlands elevate the urgency to develop domestic alternatives. With state support, Chinese domestic equipment companies have made progress; at least five Chinese producers are reportedly progressing to mass production in deposition; SMEE has created demonstration equipment in lithography; and NAURA and AMEC have entered the etching market for larger nodes.

Materials

The \$64 billion semiconductor materials market comprises chemicals and materials used in the front-end (\$40 billion) and back-end (ATP) (\$24 billion) of the supply chain. Silicon wafers and photoresist comprise about half of the total market for front-end materials (\$19.5 billion), but other subcategories, such as gases, wet chemicals, CMP slurries, and sputtering targets, are also vital to various steps of the fabrication process. Similarly, substrates and lead frames comprise about half of the back-end market (\$12.8 billion); other key subcategories include bonding wire, encapsulation resins, ceramic packages, and die attach materials.

Most leading materials companies are headquartered in Japan, the United States, and the EU (see Exhibit 11). There are multiple segments of the front-end and back-end materials market where Japan is home to at least three of the leading vendors. Still, its global production footprint is expanding to accommodate new fab capacity. In the United States, Hemlock Semiconductor, a manufacturer of hyper-pure polysilicon, invested more than \$370 million to expand its facilities in Michigan; Entegris,

a semiconductor materials manufacturer, is undertaking a \$600 million expansion of its center of excellence in Colorado Springs; Global Wafers is building a new 300 mm silicon wafer plant in Texas to supply TSMC, Intel, Texas Instruments, and Samsung; and Calumet is standing up a 60,000 square foot substrates facility in Michigan. In South Korea, Dongwoo Fine Chem announced a new photoresist line at its Iksan plant, in part to reduce reliance on imports from Japan. And in Taiwan, Entegris is building a \$500 million wet chemicals and CMP slurries plant in Kaohsiung to support today's advanced logic nodes (newer than 10 nanometers).¹⁹

The trend of co-location near fab sites is not uniform across all materials segments. Producers of low-volume, high-value, technically advanced materials, such as extreme ultra-violet (EUV) photoresist, weigh the risk of IP leakage and the difficulty of ensuring efficient, high-quality production far from their main production bases. On the other hand, materials for which production

knowledge is widely dispersed, and which incur higher logistics costs, have a greater incentive to be co-located near fabs. Examples include older generations of photoresist, purified straight chemicals such as hydrofluoric acid, and bulk gases that make localized onsite production financially attractive.

Going forward, further efforts are needed to improve resilience. A survey published in December 2023 by BIS found that industry respondents "expressed significant concern about domestic sources of three categories of materials: bare wafers, gases, and wet chemicals."²⁰ The post-COVID chip shortage also brought to the fore the sourcing challenges related to package substrates, which connect chips to the circuit boards.²¹ Additionally, certain raw materials, including gallium, rare earths, and many other critical minerals, are still largely sourced from single regions. There are efforts to source some of these critical materials by recycling from old devices, but the vast majority of mining and refining for these materials is done in Mainland China.²²

EXHIBIT 11

Market size and number of major vendors by semiconductor materials segment



1. Mainland China
Source: SEMI; IHS; BCG analysis



Assembly, Test, and Packaging

The \$95 billion ATP market is currently concentrated in Northeast Asia. South Korea hosts significant back-end capacity proximate to existing fabs. More importantly, Mainland China and Taiwan together host nearly 60% of global ATP capacity (including both IDM ATP facilities and OSATs). Out of 36 ATP facilities announced since 2020, 25 are projected to be in Mainland China and Taiwan (see Exhibit 12).²³ Due to lower construction and skilled labor costs,²⁴ this pattern is likely to persist into the near future.

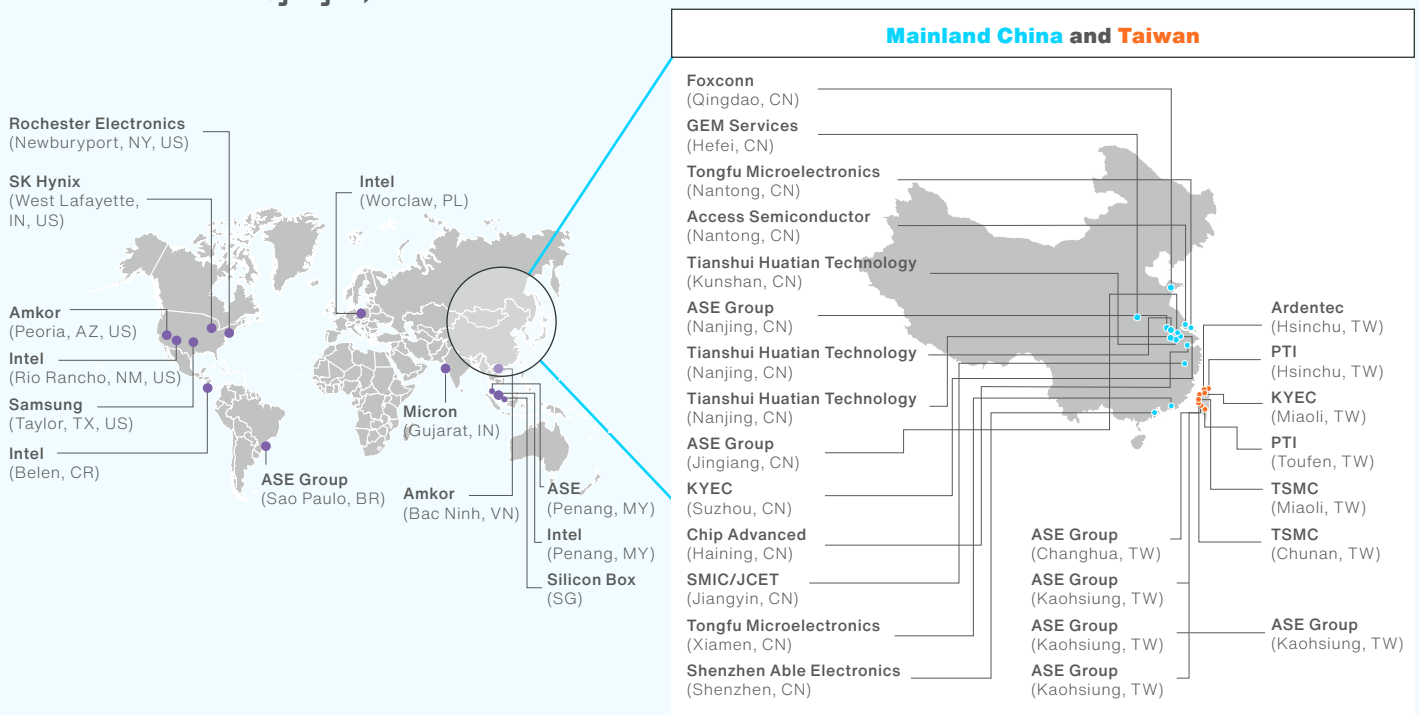
However, over the longer term, with sustained policy support and foreign investment, we expect a shift of ATP capacity toward other regions, including Latin America, Europe, and less-established parts of Southeast Asia, thereby improving resilience. Southeast Asia is already home to significant ATP activity, accounting for ~20% of total global

ATP capacity, with Malaysia capturing the greatest share within the region. Other countries expected to grow ATP capacity include Vietnam²⁵, where Amkor is investing \$1.6 billion in a 200,000 sq. meter advanced packaging facility, and Costa Rica with Intel's facility.²⁶ We forecast significant ATP capacity additions in these emerging markets, from 20% of global capacity in 2022 to 27% in 2032, primarily driven by Southeast Asia (see Exhibit 13).

The United States accounts for only a small share of global ATP capacity. Conventional packaging, which accounts for \$51 billion of the \$95 billion ATP market, is concentrated in developing countries, due to both the labor-intensive nature of the work and low margins. The United States can improve resilience foremost through expanding ATP capacity in nearby low-cost geographies as well as achieving a more equally distributed ATP facility footprint globally.

EXHIBIT 12

New ATP investments by region, 2020-2023



Mainland China

Taiwan

Rest of World

Facilities

14

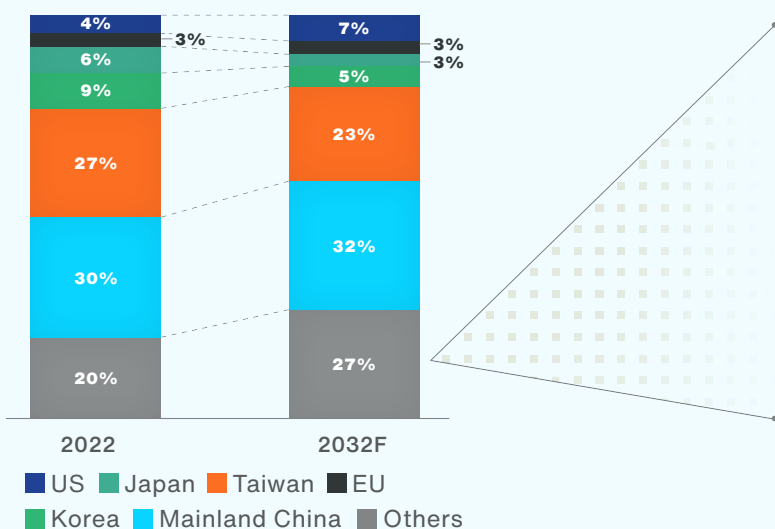
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13

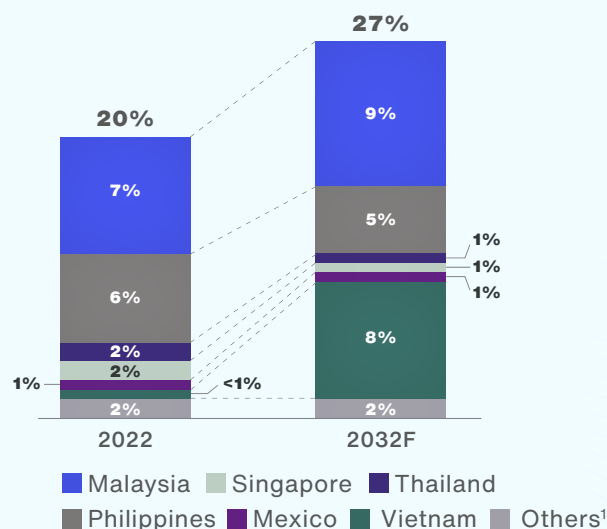
Note: Includes both IDM internal ATP facilities and OSATs
Source: SEMI; BCG Analysis

ATP capacity²⁷ distribution by region

2022–2032F global ATP capacity



Rest of world ATP capacity, 2022–2032F (as % of total capacity)



1. Other countries include Indonesia, Canada, Brazil, Costa Rica, India, Israel, and Morocco
 Note: Includes both OSAT and IDM facilities
 Source: US Department of State; The White House; SEMI; IHS; BCG analysis

Nonetheless, in advanced packaging, which accounts for just under half of the ATP market, technological breakthroughs could open the door for higher-cost regions such as the United States to play an enhanced role in ATP. A key innovation is the heterogeneous integration of chiplets (see sidebar).

To strengthen the US semiconductor supply chain, one of the goals of the US CHIPS Act is to grow the US domestic advanced packaging ecosystem. The first commercial results of this policy are emerging: Amkor announced it would stand up a \$2 billion facility in Peoria, Arizona, to package chips produced there by TSMC for Apple, and Intel will invest \$3.5 billion in advanced packaging at its Rio Rancho, New Mexico, facility. SK Hynix plans to invest roughly \$4 billion to build an advanced packaging facility in Indiana. Furthermore, Samsung is planning to construct an advanced packaging facility as part of a larger semiconductor ecosystem in Texas. Advanced packaging R&D could also be enhanced by \$3 billion from the CHIPS Act under the National Advanced Packaging Manufacturing Program (NAPMP).

SIDEBAR: Chiplets

The term “advanced packaging” covers a wide range of materials and manufacturing technologies. While this term is used to describe approximately 46% of the ATP market, a small but growing subset of this market uses highly precise and automated manufacturing methods to assemble products consisting of multiple active and passive components, namely, chiplet products.

Heterogeneous integration of chiplets is the process of combining multiple chips and chiplets to match the functionality of a single monolithic system-on-chip (SoC). Engineers can design components and adjust features on a case-by-case basis and source specific functionality from different suppliers. Although there may be tradeoffs in cost and complexity, possible benefits can include lower cost relative to a similarly capable monolithic chip, smaller form factors, greater design flexibility, and improved yields. By working with multiple vendors, companies can potentially reduce system costs and time to market.

Demand for chiplets technology is growing due to applications in computing and AI, but there are currently only a limited number of companies with the capability to assemble these packages. IDMs are beginning to adopt this technology to package newer nodes in-house, blurring the lines between fabrication and ATP.

However, there are tradeoffs to investing in chiplet technology. Acquiring the assembly technology requires higher upfront capital costs. Companies need to invest in EDA and simulation software to design and test the validity of their designs. Moreover, designing interconnected chiplets raises the design and testing complexity of semiconductor devices. Additionally, chiplets require more complex power management and thermal management solutions to handle heat.

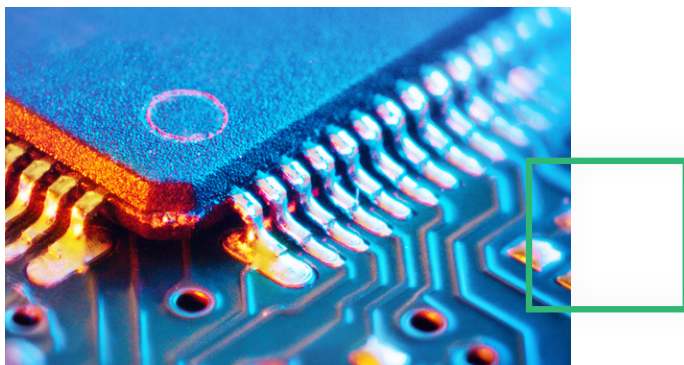
Looking Ahead—the Pathway to Greater Resilience

Sustained Support for Investment in Resiliency

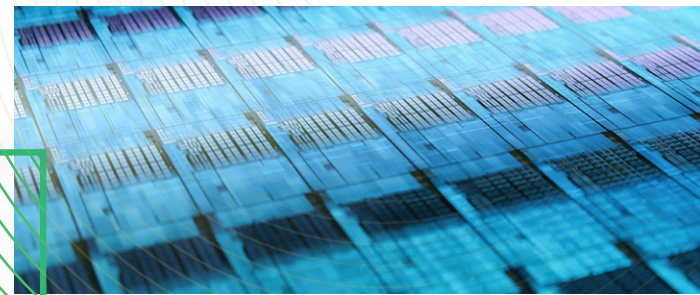
Building on the recent success of incentive programs, policymakers can continue to demonstrate a steadfast commitment to supply chain resilience. In the United States, the government can accelerate implementation of existing CHIPS Act programs. It can also consider the need for future tax incentives; for example, if the current ITC were to be made permanent and broadened to cover semiconductor design, it would make future incentives more predictable, thus helping companies make better investment decisions. In other regions, governments can likewise take actions to extend and enhance incentive programs.

Equally important, companies and governments can adopt a long-term, strategic view of resilience. The semiconductor industry is prone to cyclicality. While cycles occur in the context of steadily growing demand, reduced asset utilization can hurt the economics of capital-intensive wafer fabrication units, which quickly manifest in reduced profitability. When a cyclical downturn occurs, industry analysts with a shorter-term equity valuation focus may raise questions on how much “excess” there is in the market, and whether incentives have driven industry to build this excess. Complex product flows and unclear demand signals can make it hard to estimate “real excess” and the timing of recovery.

It will be critical in those times to “stay the course.” In a world that is becoming as heavily reliant on chips as on energy, the impact of a potential “black swan” event—such as another global pandemic—would be considerably worse than the near-term externalities of “excess.” Confident leadership and communication, by both companies and governments, will be critical.



One area of potential concern is in logic at or older than 28 nanometers. The trajectory of current fab construction puts this capacity substantially in excess of future demand



Supply-Demand Imbalances

Against the backdrop of improving resilience—driven by over \$2 trillion in wafer fab investments we expect over the coming decade—pockets of the supply chain exhibit a risk of supply-demand imbalances.

One area of potential concern is in logic at or older than 28 nanometers. The trajectory of current fab construction puts this capacity substantially in excess of future demand, with the majority of the capacity in large fabs in Mainland China. Absent some change in trajectory, the highly utilization-driven fab economics could lead to substantial pressures to reduce wafer prices, which may cause fabless companies to rethink process technology selection decisions.

New Regions in the Supply Chain

As investments in fab capacity gather momentum around the world, vulnerabilities in the form of inadequate capacity for “back-end” manufacturing—particularly in ATP—are becoming more apparent.

The entrance of new markets into the semiconductor ecosystem presents an opportunity to address these vulnerabilities in the medium to long term. Southeast Asia, in particular, can play an enhanced role. For decades, Malaysia has attracted extensive investment in ATP activities, giving rise to a thriving ecosystem. Now Vietnam, a relative newcomer, is also attracting investments from Intel, Amkor, and other companies from around the world, and is projected to increase its share of global ATP capacity from less than 1% to 9% of global ATP capacity by 2032. At a time when companies face challenges securing talent, Southeast Asia is poised to raise the number of working-age people with postsecondary schooling to 65 million in 2030, compared with 37 million in 2015.²⁸

Southeast Asia is poised to raise the number of working-age people with postsecondary schooling to 65 million in 2030, compared with 37 million in 2015

Whether new markets will realize their full potential to attract investment will depend on numerous factors, such as access to a skilled, cost-competitive workforce; availability of reliable power and water utilities; an enabling regulatory environment with limited market barriers; security and rule of law; and competitive incentives schemes. Government policy also plays a role, particularly as companies place more emphasis than ever on environmental sustainability, transparency, and social responsibility in their global operations.

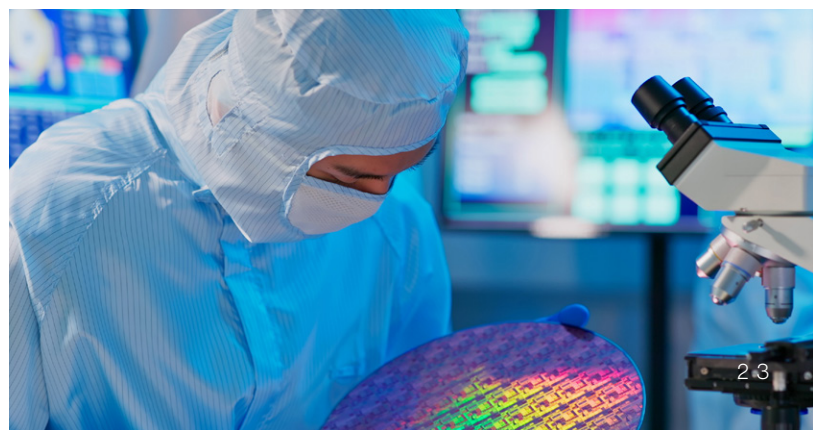
The US government is also stepping up its efforts to enable new regions to create a more diverse ecosystem in other segments of the semiconductor supply chain. The US State Department is responsible for implementing the \$500 million ITSI Fund, established under the

CHIPS Act, to expand and diversify downstream capacity in the Indo-Pacific and Western Hemisphere. A core objective is to promote “the expansion of the international assembly, testing, and packaging capacity needed to diversify the global semiconductor supply chain.”²⁹ The US government has announced ITSI partnerships with Panama, Costa Rica, Vietnam, Indonesia, and the Philippines and launched semiconductor ecosystem assessments for each country.³⁰ In September 2023, \$2 million of ITSI funding was allocated toward supporting a semiconductor workforce development initiative in Vietnam.³¹ Arizona State University’s Ira A. Fulton Schools of Engineering is cooperating with the US Department of State to support these efforts.³²

In addition, the US government is pursuing semiconductor cooperation with India, including through the bilateral Initiative for Critical and Emerging Technology (iCET) established by President Biden and Prime Minister Modi in 2022,³³ and via a 2023 US-India Semiconductor Supply Chain and Innovation Partnership Memorandum of Understanding.³⁴

Talent and Immigration

Semiconductor development and production rely on access to a workforce with diverse skill sets. As the industry’s innovation cycles and R&D investments accelerate, they will need to ensure they are taking steps to develop a pipeline of engineers and operators with the specialized skills and training to operate new semiconductor facilities. A July 2023 study by SIA, in partnership with Oxford Economics, found that the United States faces a significant shortage of technicians, computer scientists, and engineers, with a projected shortfall of 67,000 of these workers in the semiconductor industry by 2030 and a gap of 1.4 million such workers throughout the broader US economy.³⁵ Competition for high-skilled talent is fierce, with newly minted engineers often preferring to join software companies or startups over roles in the semiconductor industry.



Talent shortages are also appearing outside the upper echelons of the workforce, in vocations spanning construction workers, technicians, electricians, master welders, and pipefitters. Without these workers, semiconductor manufacturing capacity cannot be adequately built and operated. Many older workers are retiring; for example, in the welding trade, where 375,000 professionals were needed to fill job openings in the United States in 2023, the average age of an employee is 55, compared with the average age of 42 across all employees.³⁶

Education is a core solution to this challenge. SIA member companies are working with states and other partners on expanding certification boot camps, apprenticeships, and other training programs at community and technical colleges located near new and expanding semiconductor fabs as an effective means to help close the workforce gap for technicians.³⁷ For example, in the United States, New Mexico has agreed to grant Intel up to \$5 million to train hundreds of new hires to support the multi-billion-dollar expansion of its Rio Rancho plant tied to chiplet manufacturing.³⁸

Welcoming foreign talent is also key to bridge the gap between talent shortages and surpluses across regions. A 2022 study by the United Nations Development Program, for example, forecasted the number of postsecondary

graduates in India and Southeast Asia’s workforce to nearly double between 2015 and 2030, to 206 million.³⁹ A micro-study by the Australian Strategic Policy Institute on the trajectories of some 500 leading semiconductor research scholars further illustrated this point.⁴⁰ Many of these scholars received STEM undergraduate degrees in Asia, earned their postgraduate degrees in the United States and the EU, and then opted to pursue their careers in the United States and the EU (see Exhibit 14). Such globally mobile career paths are vital to the industry’s success today.

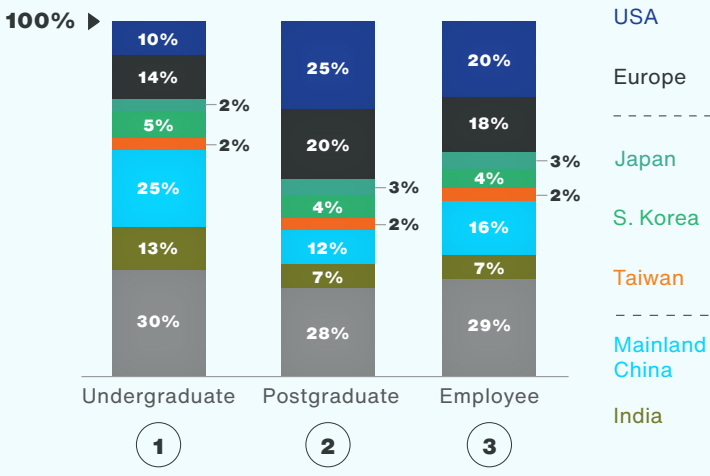
For the United States, the opportunity lies in improving its aggregate foreign talent retention. SIA has found that at US colleges and universities, over 50% of master’s engineering graduates and over 60% of PhD engineering graduates are foreign citizens. Among foreign students who graduate from a US institution, approximately 80% of master’s and 25% of PhD STEM graduates do not remain in the United States after graduating, either by choice or because of US immigration policy.⁴¹

Germany is a leading example of how to encourage both high-skill and mid-skill migration. In July 2023, the German government passed the Skilled Immigration Act, which eases the process to receive a visa for individuals who earn over €39,600 and for those looking for work through an “Opportunity Card.” Additionally, Germany has removed caps on visas for high-skilled workers.

EXHIBIT 14

High-skilled workers migrate between geographies during their careers

Top authors of advanced IC papers
Location at different career stages



	1	2	3	Trend
USA	+15%pt	-5%pt		<ul style="list-style-type: none"> Top destinations for postgraduate studies Large net inflow of STEM talent from rest of world
Europe	+6%pt	-2%pt		
Japan	+1%pt	--		<ul style="list-style-type: none"> Impressive retention across all stages Struggle to attract foreign talent
S. Korea	-1%pt	--		
Taiwan	--	--		
Mainland China	-13%pt	+4%pt		<ul style="list-style-type: none"> Top talent trains abroad ...and stays abroad, aside from some returners
India	-6%pt	--		



Note: N=459 1. Mainland China
Source: Australian Strategic Policy Institute (ASPI); Expert interviews; ProtectAZWorkers; BCG analysis

Open Trade and Cooperation

The global semiconductor supply chain faces a world of heightened tension and complexity. Military conflicts can disrupt pockets of the supply chain and lead to shortages (for example, the disruption to neon gas supplies used in semiconductor manufacturing lasers following Russia’s invasion of Ukraine). Non-military disputes can also impact global production chains; in 2019, for instance, a disagreement between Japan and South Korea led Japan to impose export controls on South Korea for materials critical to semiconductor production, such as hydrogen fluoride, fluorinated polyamide, and photoresist. Floods, fires, and other climate-related disasters, as well as more frequent pandemics, also pose “black swan” risks.

Global trade in semiconductor-related products and services remains substantial. Global trade in semiconductor chips, in real dollars, grew by 43% between 2017 and 2022. While the

US share of global exports has decreased, Mainland China’s share continues to increase (see Exhibit 15). Mainland China still runs a large trade deficit in semiconductors, but relative to its total trade, the deficit has declined across most semiconductor products.⁴²

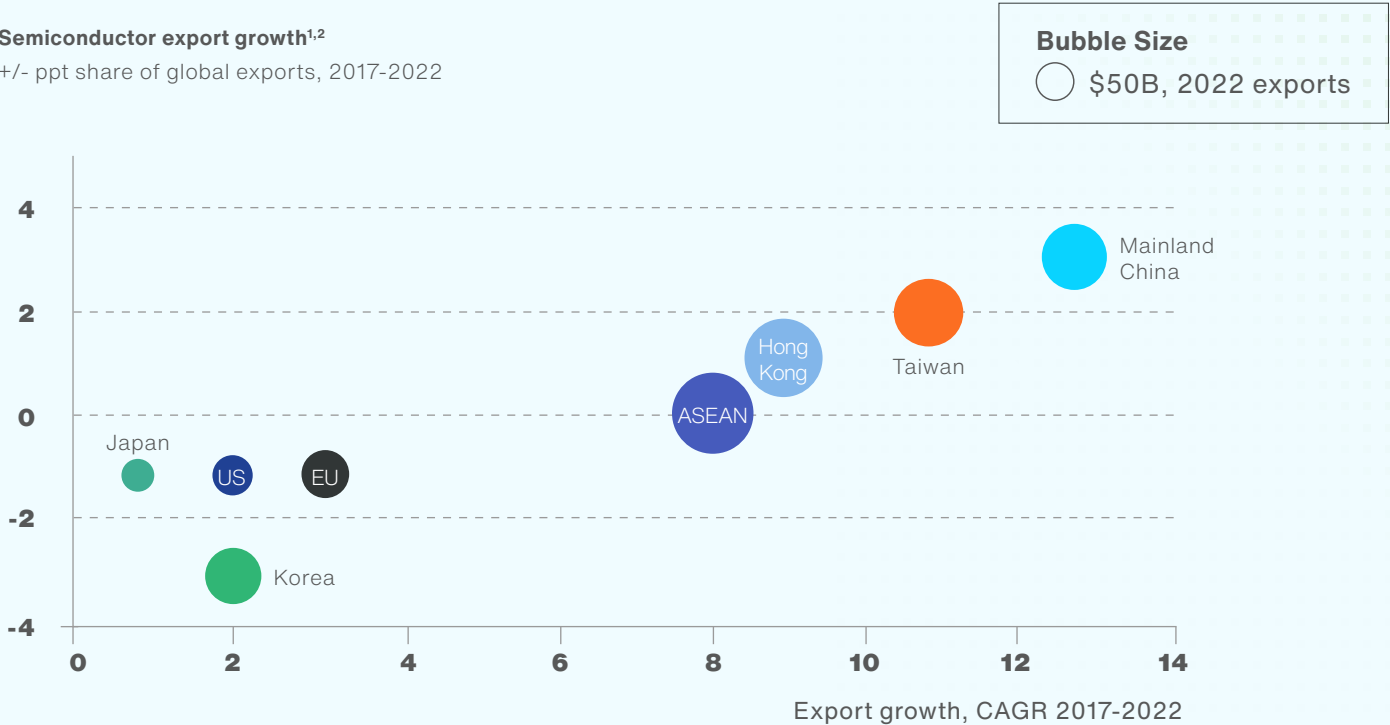
Ongoing geopolitical tensions between the United States and Mainland China drive significant uncertainty for companies engaging in the global semiconductor ecosystem. The world’s leading semiconductor companies—in wafer fabrication, design, materials, and equipment—still generate a significant share of their revenues in Mainland China. A March 2020 BCG report entitled “How Restricting Trade with Mainland China Could End US Semiconductor Leadership” found that a full technology decoupling from Mainland China would lead to the US semiconductor industry losing its current sales and innovation leadership position and 15,000 to 40,000 highly skilled direct jobs in the industry.

EXHIBIT 15

Global growth in semiconductor product exports by region, 2017-2022

Semiconductor export growth^{1,2}

+/- ppt share of global exports, 2017-2022



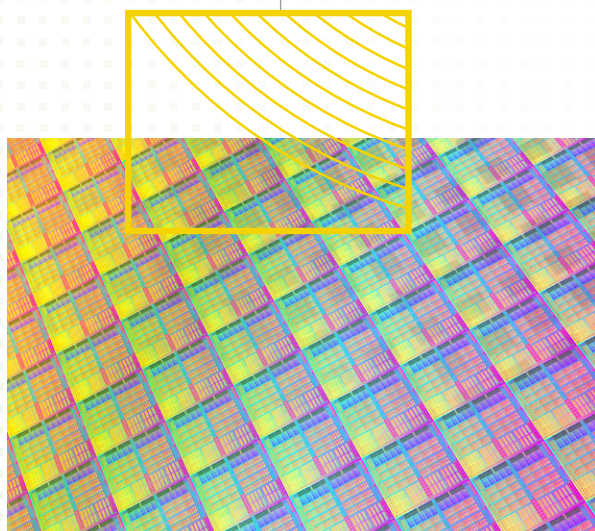
1. HS codes 854110, 854121, 854129, 854130, and 8542, excludes semiconductor equipment

2. Real 2017 USD.

Source: S&P Global Trade Atlas, UN Comtrade; BCG analysis

Global trade in semiconductor chips, in real dollars, grew by 43% between 2017 and 2022.

Mainland China is working to ensure its domestic companies have ready access to foreign markets to sell their semiconductor products. Mainland China has bilateral investment agreements with over 100 countries, including many across Europe and Asia.⁴³ Mainland China by year-end 2021 had active free trade agreements with 26 countries and territories and was actively negotiating another eight agreements. Mainland China is part of the Regional Comprehensive Economic Partnership (RCEP) that entered into force in 2022, which convenes 15 countries across Association of Southeast Asian Nations (ASEAN), South Korea, Australia, New Zealand, and Japan—economies that represent around 30% of global GDP.⁴⁴ RCEP is widely viewed as an alternative to the Trans-Pacific Partnership (TPP), a US-led agreement that was the cornerstone of the US strategic pivot to Asia in the early to mid-2010s, but that the United States withdrew from in 2017.



The US government has been less active in furthering its trade agenda. It has no active Free Trade Agreement (FTA) negotiations, its recent achievements being the 2018 US-Mexico-Canada Agreement (USMCA)—a renegotiation of the 1994 North American Free Trade Agreement (NAFTA)—and a digital trade agreement with Japan concluded in 2020. The Indo-Pacific Economic Framework, a US-led economic arrangement with 13 countries in Asia, is not a conventional, comprehensive FTA with chapters on tariffs, non-tariff barriers, investment, IP, and other provisions of greatest concern to companies.⁴⁵

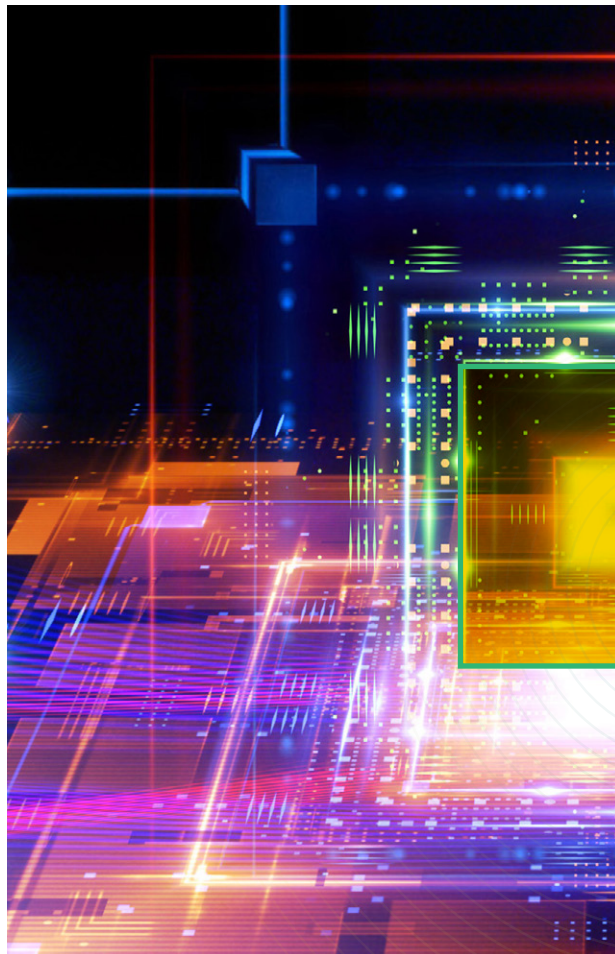
Future Needs of the Industry

Semiconductors will play a critical role in the global economy in the decade to come, from everyday products to the cutting edge in defense and AI. Few industries have a supply chain and ecosystem as complex and globally intertwined. And yet, a number of factors—from geopolitical tensions and a more complex regulatory environment to labor shortages and rising costs—have underscored the need for supply chain diversification and investments to improve resiliency.

Governments, likewise, have recognized the strategic importance of semiconductors and seek to reduce strategic dependencies by attracting and incentivizing new domestic or “near-shored” investments to achieve resilience. But resilience is not synonymous with self-sufficiency, and, as we laid out in our April 2021 report, the costs of self-sufficiency are staggering.

For the semiconductor industry to thrive, key future needs include the following:

- *Fostering talent* at all levels, from cutting-edge research to technicians on the factory floor and welders on construction sites, through effective partnering with educational institutions, workforce training, and industry-tailored migration policies
- *Providing sustained policy support* to address remaining supply chain vulnerabilities, anticipate the expiration of current incentive programs, and “stay the course” through business cycles
- *Helping new markets develop the right conditions to attract semiconductor investment*, including targeted and sustained use of incentives, workforce training, infrastructure buildout, and improvements in the regulatory environment
- *Maintaining open trade and diversifying end markets* by enacting trade measures that are well-defined, consistently applied, and aligned across likeminded partners, and negotiating effective trade agreements in the face of geopolitical uncertainty



Appendix

Description of Government Initiatives

United States

The United States leads the world in chip design and is home to leading global chipmakers, but all advanced logic chip fabrication (<10 nanometers) is located in Asia, and 97% of ATP is performed outside the United States.⁴⁶ US policymakers and corporate leaders both inside and outside the semiconductor industry recognize the urgency and opportunity to strengthen resilience in the United States and global semiconductor supply chains and reduce certain strategic dependencies.

Enacted in August 2022, the CHIPS Act appropriated over \$52 billion in funding to support the semiconductor industry, including \$39 billion in grants for manufacturing (with \$2 billion set aside for technology nodes at least as old as 28 nanometers and \$3.5 billion set aside for the creation of a “secure enclave” Defense Department program) and \$11 billion in funding for R&D and workforce development. The bill also appropriated \$500 million to the ITSI Fund, which is aimed at improving resilience in the assembly, packaging, and testing stage of the supply chain, among other focus areas.⁴⁷ The enactment of the law, including a 25% semiconductor manufacturing ITC, has sent a strong signal to the market, spurring private sector investments in the United States. Since 2020, when the CHIPS Act was first passed, the United States has attracted over \$350 billion in private investment for semiconductor manufacturing, materials, and equipment,⁴⁸ and companies are already leveraging the 25% ITC for chip manufacturing.

US states are also implementing policies to attract semiconductor investments. Examples include the following:

- Colorado created a \$75 million CHIPS Refundable Tax Credit program and the CHIPS Zone program, which gives semiconductor companies access to five tax credits that can be earned by investing in equipment, staff, and R&D. The state also provides support for workforce development plans through the \$85 million Opportunity Now Grant Program, and it established an express-lane for air permitting of semiconductor projects.⁴⁹

- New York’s Green CHIPS project includes a state ITC of up to 5% of qualified investments, an R&D credit of up to 8% of expenditures, and a jobs tax credit of up to 7.5% of gross wages per new job.⁵⁰
- Arizona allocated a \$100 million investment to spur greater growth in semiconductor industry, managed by the Arizona Commerce Authority to further enhance infrastructure and workforce and research capabilities.⁵¹
- The Texas CHIPS Act, approved in June 2023, creates a \$698 million fund to issue grants to private companies with an established presence within the state to encourage economic development related to semiconductor manufacturing and design. The Act also appropriated more than \$660 million for the creation of advanced R&D centers at universities.⁵²
- The Oregon CHIPS Fund, approved in April 2023 with initial funding of \$190 million, awards grants and makes loans to businesses applying for federal semiconductor financial assistance for developing manufacturing facilities, conducting R&D, and partnering with institutions of higher education.⁵³
- California has several programs targeting the semiconductor industry through tax incentives and credits to promote both semiconductor manufacturing and R&D. For example, its California Competes Tax Credit provides over \$180 million in credits annually, and its R&D credit can be applied on up to 39% of qualified expenses.⁵⁴

Mainland China

The Chinese government is adopting a whole-of-nation approach to promote its semiconductor industry, as reflected in its five-year and other long-term planning documents. Mainland China has engaged in a decade-long effort⁵⁵ to subsidize, including through equity infusions and domestic manufacturing capacity for logic chips at or older than 28 nanometers, which are used in a variety of end-use markets including aerospace & defense, automotive, industrial applications, and medical devices. The Chinese government has documented its ambitions for Mainland China to become a global leader in the semiconductor industry. The 2014 *Guidelines for the Development and Promotion of*

the Integrated Circuit Industry (IC Guidelines) set the goal of mass producing chips at or newer than 16/14 nanometers by 2020, and by 2030, ensuring that “the main linkages in the semiconductor supply chain reach the internationally advanced level, and a group of enterprises enter the global top ranks.” A year later, in 2015, Mainland China published the Made in China 2025 Plan, which sets aspirational goals for Mainland China to achieve 70% self-sufficiency in semiconductors by 2025.

Central to Mainland China’s semiconductor industrial policy is the National Integrated Circuits Industry Development Investment Fund, hereafter referred to as the National IC Fund,⁵⁶ established in 2014. Mainland China has administered two phases of the National IC Fund and is in the process of beginning Phase III (see Exhibit 16). Phase I (2014) raised over \$20 billion in state-

backed financing in support of fabrication and design activities. Phase II (2019) raised an additional \$32 billion, with a greater focus on supporting older node fabrication projects⁵⁷ and design activities, and increasingly also to equipment and materials investments. Phase III (as of 2023) aims to raise a record \$40 billion, with manufacturing equipment a likely priority in support of Mainland China’s self-sufficiency goals. Beyond the National IC Fund at the central level, at least 15 provincial and municipal funds have been created since 2015, raising some \$50 billion in capital. In addition, local governments typically provide land, utilities, and other inputs at below cost for semiconductor manufacturing sites. Other Chinese government incentives tailored to support its domestic semiconductor sector include grants, reduced utility rates, favorable loans, significant tax breaks, and free or discounted land.⁵⁸

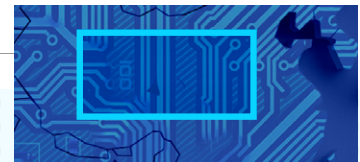
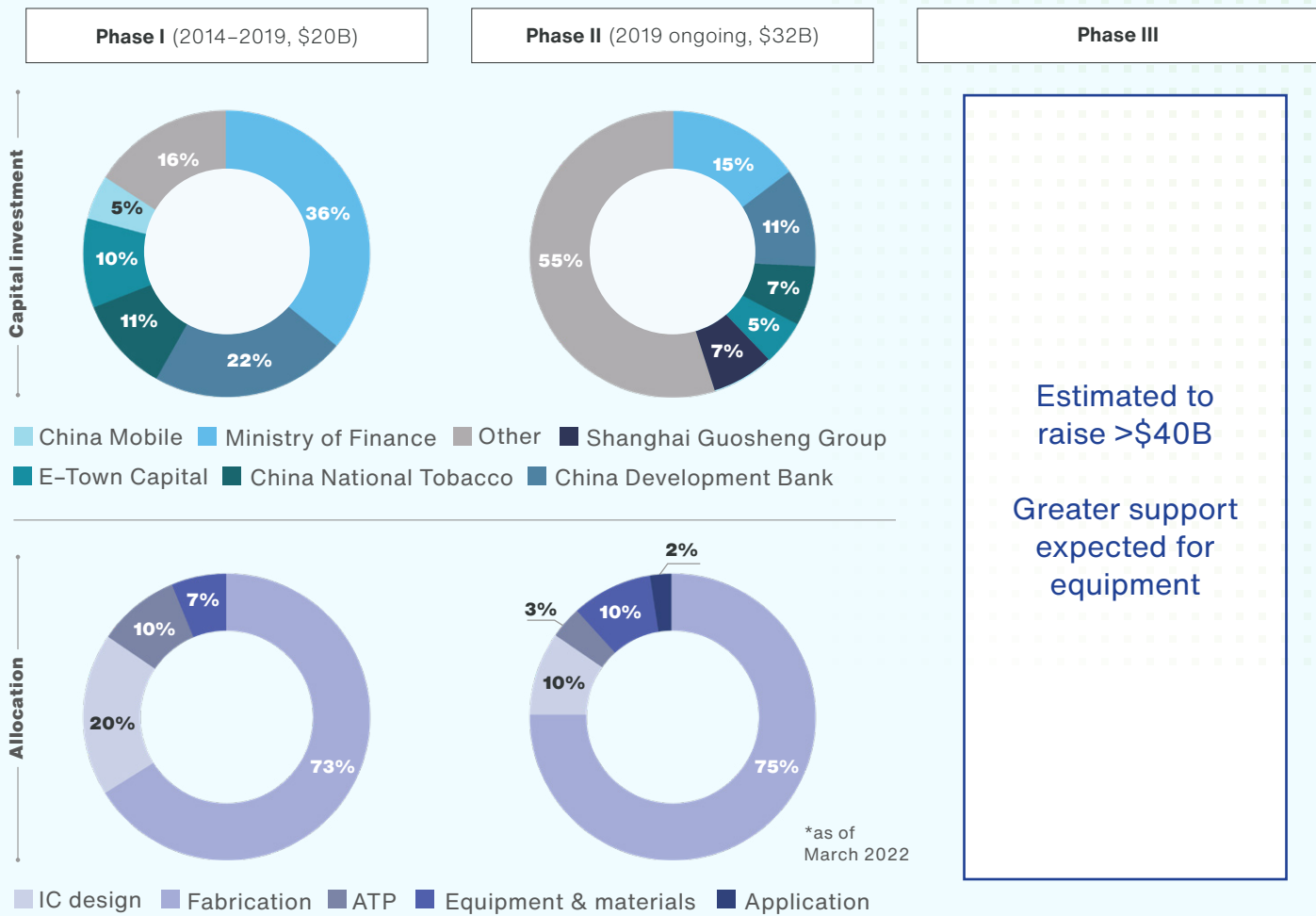


EXHIBIT 16

Mainland China National IC Fund Phases with capitalization and capital allocation



Source: Bruegel; Citic Securities ; BCG Analysis

As a result of this government support, a 2020 study by BCG and SIA found that, all else equal, the cost of building and operating a fab in Mainland China is 37% lower than doing so in the United States.⁵⁹

Mainland China leads the world in ATP capacity and wafer fabrication for logic chips at or older than 28 nanometers. In the past five years alone, Chinese companies have invested \$63 billion in 73 fabs, primarily in fabs for chips over 28 nanometers, supported by significant subsidies from the Chinese government.⁶⁰ It is also rumored to be making strides in newer advanced logic nodes.⁶¹

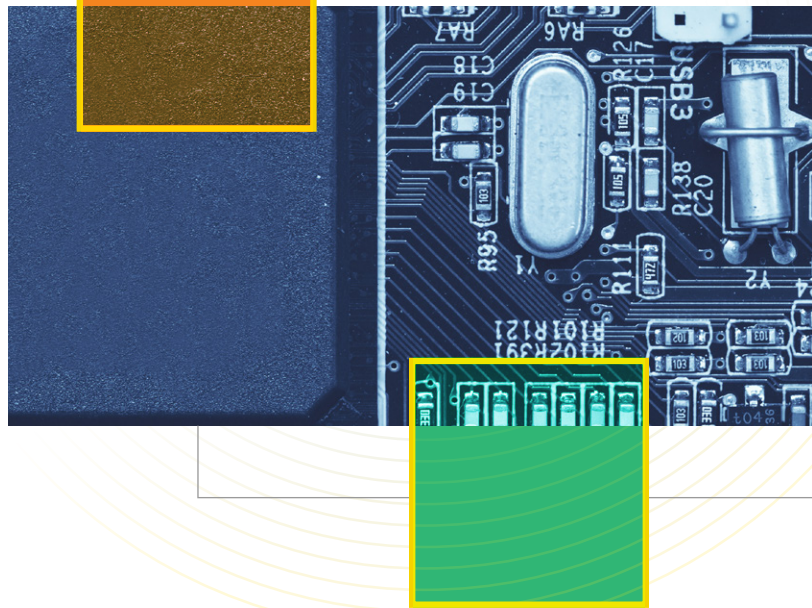
Mainland China is also a leading producer of minerals and other industrial raw materials used for chip manufacturing. It is making moderate progress in design, core IP and EDA, and equipment for advanced node chips, but is challenged by export controls on advanced lithography equipment recently imposed by the United States, Japan, and the Netherlands.

Europe

The European Union is a global leader in advanced equipment manufacturing, led by ASML, a producer of advanced EUV lithography equipment. However, Europe's share of global fabrication capacity sits below 10%. The European Commission in 2021 unveiled the Digital Compass 2030, with a stated goal to increase this share to 20% by 2030.⁶²

The EU's strategy⁶³ for semiconductors, under the umbrella of its Digital Compass strategy, comprises three pillars. First, the Chips for Europe Initiative targets design capabilities, production innovation (for example, 3D heterogeneous system integration back-end processes), and talent. The second "Security of Supply" pillar focuses on filling a proven funding gap to develop a "first of a kind" that fabricates nodes below 2 nanometer or substrate material production (for example, SiC, GaN). Lastly, a monitor and crisis reporting pillar creates a legal basis for "common purchasing" and "priority orders" among EU member states.

The EU Chips Act, enacted in September 2023, seeks to mobilize \$47 billion in public and private funds via three funding mechanisms: Invest EU, the European Investment Bank Group, and the European Innovation Council. However, EU Member State governments will disburse subsidy packages under EU state aid rules, which so far has resulted in the majority of funding concentrated in wealthier member states such as Germany and France. Notably, the EU Chips Act allows member states to disburse larger amounts to underdeveloped regions, making these attractive locations for investment.



The EU's efforts are yielding results. For example, Intel plans to expand the scope of its Magdeburg Fab from \$17 billion to \$33 billion, supported by a \$10.9 billion subsidy package from Germany that may include state aid and caps on energy costs.⁶⁴ Infineon announced a \$5 billion investment in Dresden, and TSMC, Bosch, Infineon, and NXP have established the European Semiconductor Manufacturing Company (ESMC) GmbH joint venture in Dresden under the European CHIPS Act.⁶⁵ France also announced plans to disburse \$3.1 billion in state aid to support STMicroelectronics' and Global Foundries' \$7.5 billion investment in Crolles.⁶⁶

The EU has an active trade policy agenda, with 47 active preferential agreements with 79 trading partners. It also has nine agreements either under negotiation or in the process of being ratified, including with India, South Korea, Indonesia, and Mexico.

Taiwan, South Korea, and Japan

Taiwan and South Korea hold strong positions in semiconductor manufacturing and continue to elevate support for their respective industries. Taiwan boasts a thriving semiconductor ecosystem, underpinned by heavy investment in R&D and TSMC's state-of-the-art foundry business. Taiwan has captured over 70% of advanced node (<10 nanometers) chip manufacturing as the go-to foundry partner for fabless companies.⁶⁷ South Korea invested early in the development of its semiconductor industry and supported the growth of Samsung and SK Hynix into global semiconductor leaders; together, they majority share in the global NAND flash memory and DRAM chips markets, respectively.⁶⁸

Taiwan has directed its efforts toward innovation and talent. Taiwan’s most recent round of investment, known as the “Taiwan Chip-based Industrial Innovation Program Industrial Innovation Program,” came into force in November 2023, allocating \$9.2 billion in funding for 2024 to 2033. Its tax incentives include a tax rebate of up to 25% for R&D activities in logic chips and a 5% tax credit on equipment used in advanced manufacturing processes. The Act has the following four main pillars:

- 1 Integrating generative AI and semiconductor technologies to drive innovation across all sectors of the economy
- 2 Attracting global R&D professionals and developing domestic talent
- 3 Accelerating the integration of new innovations into all segments of the semiconductor supply chain, prioritizing <1 nanometer node silicon-based chip manufacturing, non-silicon-based chip manufacturing, 3D chip stacking, and heterogeneous integration
- 4 Attracting IC startups to land in Taiwan by providing tools, IP, masks, and tape-out services, as well as funding and partnership opportunities with local industry leaders⁶⁹

In 2021, the Ministry of Education also enacted the Training Act to address the need for talent in emerging high-tech industries, including semiconductors.⁷⁰ Among other things, the Act relaxed some educational regulations to foster industry-academia collaboration, and since then, the public and private sector have joined forces to establish six semiconductor research institutes across the island.

South Korea in 2021 unveiled the K-Belt Semiconductor Strategy, aimed at attracting up to \$450 billion of investment, strengthening manufacturing capabilities, and expanding in the logic sector. South Korea’s incentive programs focus on tax incentives, expected to yield \$55 billion–\$65 billion in relief for companies. The tax credit relief ranges by size of enterprise and supply chain activity, offering up to 50% tax credit for R&D and 25% for manufacturing activities, and an additional 10% deduction for investments in 2023.^{71 72}

These programs are spurring new investment commitments. For example, in 2022, SK Hynix announced plans to build M15X Fab in Cheongju, encouraged by the K-CHIPS Act tax credit.⁷³ In 2022, equipment maker ASML also selected South Korea as the new location

of a \$180 million site for equipment repair, R&D, and training related to EUV lithography.⁷⁴

Amassing 50% global market share at its height in the 1980s, Japan now only represents 9% of the global semiconductor sales. Japanese companies lag behind leading-edge logic manufacturing companies by a decade, manufacturing chips only as advanced as 40 nanometers.⁷⁵ The government now aims to address this gap by making a technological leap into advanced logic manufacturing in the next five years. Japan’s Strategy for Semiconductors and the Digital Industry announced in 2021 aims to increase sales of semiconductors from \$38 billion in 2020 to \$112 billion by 2030. To drive implementation of this goal, the government introduced both the 5G Promotion Act⁷⁶ and the Act on the New Energy and Industrial Technology Development Organization in 2022 to develop fabs for high-speed processing semiconductors. In November 2021, the Japanese government allocated \$4.1 billion for domestic investments in leading-edge chip manufacturing capacity and in November 2023 announced an additional \$13 billion funding allocation to attract investment.

Japan has also taken significant steps to support fab construction. At least \$3.5 billion of the \$8.6 billion in costs to build TSMC’s joint venture with Sony, DENSO, and Toyota in Kumamoto are being covered by the government, the first project to receive a grant from a \$4 billion public fund administered by Japan’s Ministry of Economy, Trade and Industry to strengthen Japan’s semiconductor industry.⁷⁷ The government also agreed to provide up to a \$620 million subsidy for Kioxia and Western Digital’s joint venture to construct Yokkaichi Fab 7, and a \$1.3 billion subsidy for Micron to expand capacity at its plant in Hiroshima.⁷⁸

Moreover, Japan is supporting leading-edge chip innovation through Rapidus, a consortium backed by Japanese companies, IBM, and European nanoelectronics research hub Interuniversity Microelectronics Centre (IMEC), aimed at producing 2-nanometer chips. The Japanese government in April 2023 granted Rapidus \$1.94 billion to support R&D activities and \$530 million in startup aid.⁷⁹

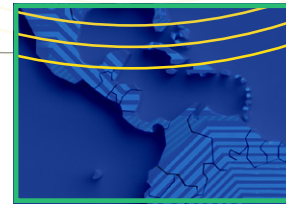
On trade policy, Japan has 18 active economic partnership agreements—including with Mainland China, the European Union covering its 27 Member States, and the 10 members of ASEAN—which provide its semiconductor companies with preferential access to those markets.

New markets

A number of new markets across Asia and the Western Hemisphere see an opportunity to attract semiconductor industry investment and have announced, or plan to announce, national semiconductor strategies and incentives programs in a bid to play a larger role in the global supply chain.

In Southeast Asia, governments have taken a variety of actions to boost incentives, including the following:

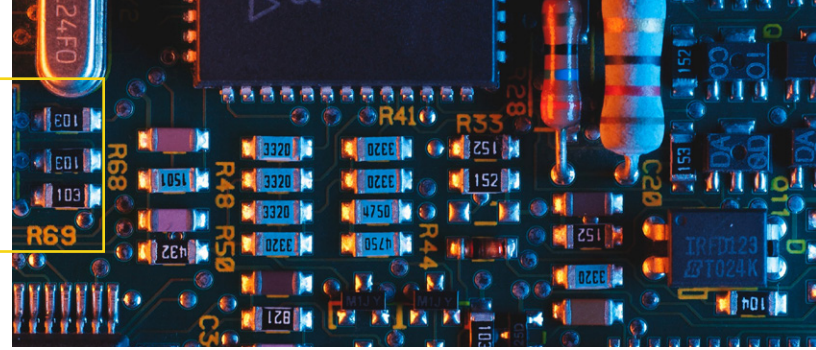
- **Vietnam.** In October 2023, the country set a goal of training 50,000 engineers by 2030 to support the semiconductor industry and plans to issue a national semiconductor strategy in early 2024. In Vietnam, Samsung invested \$850 million in a Flip-chip Ball Grid Array (FCBGA) production facility and Amkor stood up a \$1.6 billion advanced packaging facility.
- **Philippines.** The government is actively enhancing workforce readiness and offering incentives through the CREATE Act for high-impact projects with a minimum investment of PhP50 billion or significant job generation. In addition to supporting the United States in ATP, there's a focus on moving up the supply chain, including in design, to stay globally competitive, with SEIPI proposing a Science and Technology Center for this purpose.⁸⁰
- **Indonesia.** The nation has designated the semiconductor sector as a priority industry eligible for tax incentives. Furthermore, the country provides additional benefits, including tax exemptions and flexible licensing, within its 19 Special Economic Zones and offers tailored investment facilities, including rent-free leases, in a newly developed integrated industrial park.⁸¹
- **Malaysia.** Its New Industrial Master Plan (NIMP) 2030 aims to enhance the manufacturing sector's value added by diversifying exported products, focusing on encouraging front-end activities such as semiconductor equipment manufacturing, wafer fabrication, and integrated circuit design. Notably, major investments from Intel (\$7 billion) and Texas Instruments (\$3.1 billion) reflect the country's attractiveness for complex manufacturing, with Intel's expansion including its first overseas 3D chip packaging facility.⁸²



In the Western Hemisphere, Costa Rica enacted Law 10234 in February 2023, which offers incentives to attract foreign investment in ATP and other semiconductor manufacturing services. Costa Rica has an existing semiconductor industry footprint largely due to the presence of Intel, which has operated in the country for decades and recently announced plans to spend \$1.2 billion to upgrade its existing ATP facility.⁸³

In December 2021, India launched its “Semicon India Programme,” which includes \$10 billion in funding for fiscal incentives,⁸⁴ and financial incentives and design infrastructure to domestic companies, startups, and Micro, Small, and Medium Enterprises (MSMEs) focused on design. To date, India's efforts have had mixed success. A joint venture between Foxconn and India's Vedanta to build a semiconductor fab, for example, did not succeed, due to complications with administrative approvals and other factors.⁸⁵ Micron, however, is proceeding with a \$825 million investment in a new chip assembly and test facility in Gujarat, with substantial support from the central and state governments.⁸⁶

The US ITSI Fund is focused on helping new markets assess their semiconductor ecosystems and target their efforts at attracting investment in areas that play to their strengths and underlying competitiveness.



Methodology

Fab Capacity

The fab capacity forecast was done by forecasting future CapEx by region and process type and allocating it to different regions based on investment patterns we observed with future fab announcements (comprising over 100 individual fabs between 2024 and 2032). This accounts for how CapEx is distributed from HQ region (the source of the investment) to destination region (where the investment is directed toward). This new capacity was added onto the existing base of capacity and thus we created a forecast for fab capacity through 2032.

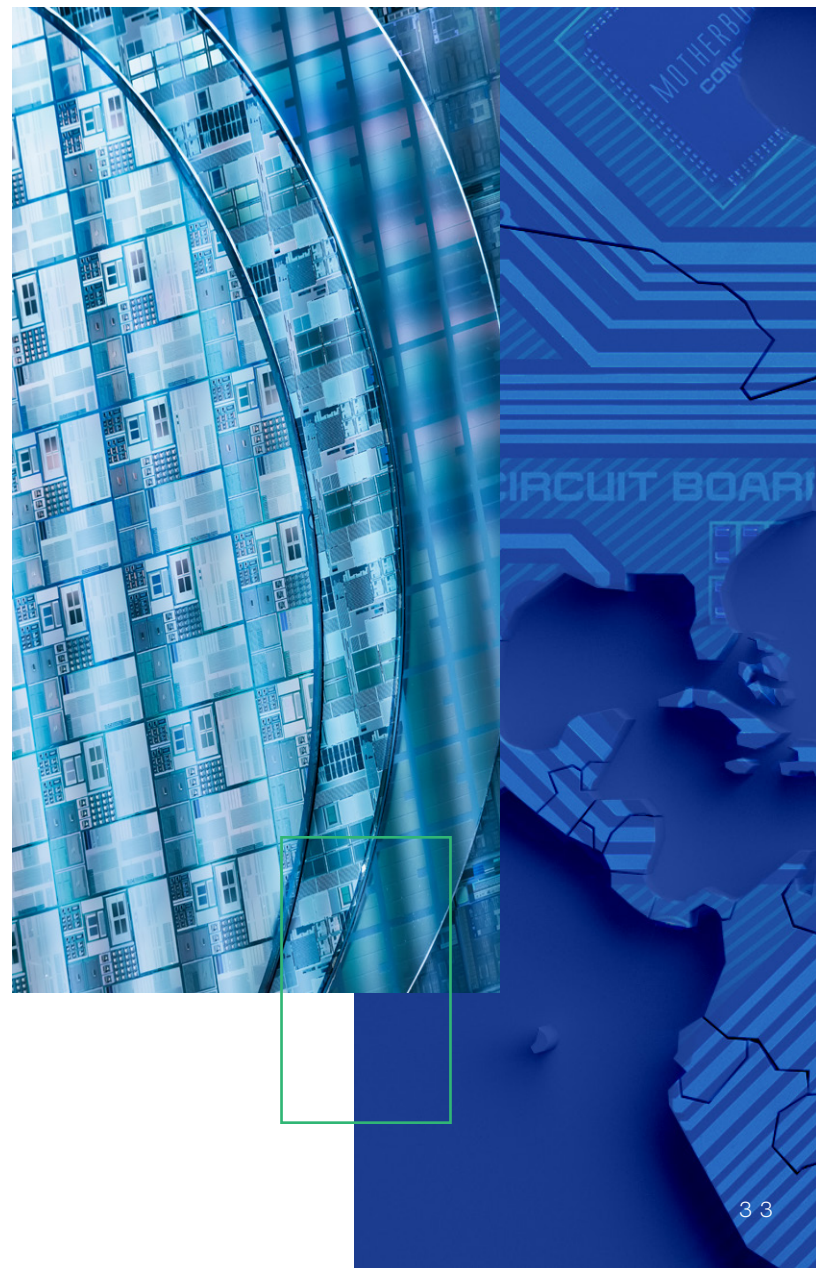
The definitions of advanced, mature, and legacy logic were collated from the Department of Commerce and previous SIA-BCG reports. In our forecast, we divide logic into (1) <10 nanometers, (2) ≥ 10 nanometers and <28 nanometers and (3) ≥ 28 nanometers.

In our September 2020 report, we presented a sediment chart of wafer fabrication capacity by region, dating to 1990. We defined capacity as (1) wafer size at or above 8 inches; (2) 50%+ probability; (3) facilities with 5000 or more wafer starts per month. Based on this methodology, certain capacity was excluded; in particular, capacity below 8 inches, which was prevalent in some regions in the 1990s, was excluded. We recognize that this significantly influenced the percentage share of capacity distribution by region for that historical period, as depicted in the sediment chart.

However, to maintain a consistent methodology, and given that the above parameters represent nearly all capacity installed today and for the foreseeable future, this report adheres to the same methodology used in the September 2020 report.

Assembly, Test, and Packaging

The ATP forecast relies on expectations of future plants based on announced investments to add to capacity. Following this, we adjust for the attractiveness of certain regions based on key cost factors (labor, construction, etc.) and nearshoring (some regions will be more attractive to locate ATP facilities near due to increasing fab capacity in those regions).



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