



Establishing Leadership in Advanced Logic Technology

What Would It Take?

November 2021

By Raj Varadarajan, Ramiro Palma, and Antonio Varas

Boston Consulting Group partners with leaders in business and society to tackle their most important challenges and capture their greatest opportunities. BCG was the pioneer in business strategy when it was founded in 1963. Today, we work closely with clients to embrace a transformational approach aimed at benefiting all stakeholders—empowering organizations to grow, build sustainable competitive advantage, and drive positive societal impact.

Our diverse, global teams bring deep industry and functional expertise and a range of perspectives that question the status quo and spark change. BCG delivers solutions through leading-edge management consulting, technology and design, and corporate and digital ventures. We work in a uniquely collaborative model across the firm and throughout all levels of the client organization, fueled by the goal of helping our clients thrive and enabling them to make the world a better place.

Contents

02 | Executive Summary

04 | What happened to US leadership in advanced logic technology?

08 | What would it take to reestablish technology leadership in the US?

15 | Conclusion

Executive Summary

Advanced logic technology is critical for the national security and economic progress of any developed economy. For example, advanced logic chips are essential for seven of the ten technologies identified as strategic in a bipartisan bill to enhance US innovation and global competitiveness passed by the US Senate in June 2021¹, as well as for several priority defense system modernization programs. In Korea, the government is making preemptive investments in infrastructure for advanced logic technology to further strengthen its domestic ecosystem. In Japan, officials have pushed the importance of reducing the cost and promoting access to advanced logic chips. And in Europe, competitiveness and technology sovereignty are top reasons for investing in a state-of-the-art European chip ecosystem, to ensure security of supply and develop new markets for groundbreaking technology.

Access to leading-node manufacturing (which today corresponds to the manufacturing nodes of <10nm) is critical to produce the most advanced logic chips. Until 2018, the US led the world in advanced technology needed to develop leading nodes. Today, while still a global leader in semiconductor sales and value-add overall, the US depends heavily on East Asia for the manufacturing portion of the value chain. And this dependence is particularly significant for leading-node manufacturing, where 90% of the total global capacity is currently concentrated in Taiwan. The recent push to attract global semiconductor manufacturing leaders to invest in building fabs in the US does accomplish one key goal—it reduces the risk of supply disruptions.

However, if the US wants to reclaim strategic advantage, the US will need to go beyond increasing share of manufacturing and reestablish US leadership, in advanced logic technology. In other words, to establish leadership the US needs both increased capacity *and* capability in advanced logic technologies.

The next few years present an important opportunity to reestablish this leadership, as the industry makes several major transitions in advanced technology, (such as gate-all-around (GAA) transistor architecture and next generation of extreme ultraviolet (EUV) lithography). These new technologies, expected to be introduced starting in 2024-2025, still require significant R&D to turn them from scientific developments into viable manufacturing processes. In addition, based on analyst forecasts, by 2030, at least 45 leading-node fabs—each with capacity of 35,000 wafers per month (wpm)—will need to be built to meet expected growth in chip demand.

Reestablishing US leadership in advanced logic technology involves three essential interrelated elements:

- Regaining manufacturing *process technology leadership* with IP and know-how based in the US to enable new leading-nodes
- Aggressively building US-based leading-node *fab capacity*—enough fabs for the US to sustain ongoing investments needed to maintain technology leadership
- Developing complementary *advanced packaging capabilities*, which are increasingly needed to make the most powerful logic devices, with state-of-the-art facilities in the US

These three essential elements to achieve technology leadership depend on a dozen enabling factors (which we discuss in detail in an upcoming report). But, our analysis indicates that the US is currently behind Taiwan and South Korea in six of these areas.

The most critical gaps are in:

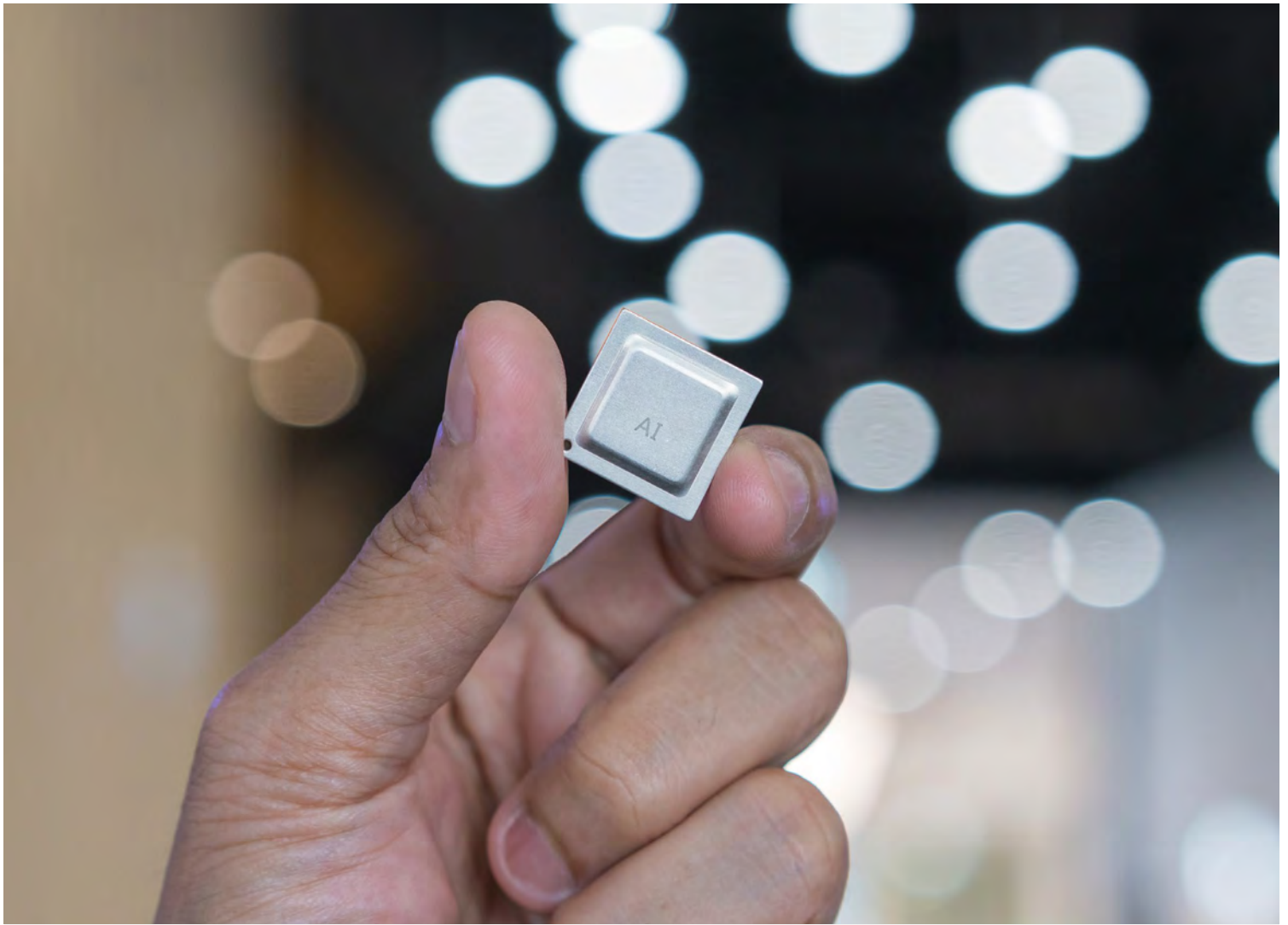
- 1 Fab cost—over ten years it is approximately 30% more costly to build and operate fabs in the US relative to other countries with advanced logic technology, due primarily to government incentives available elsewhere.
- 2 Public funding for R&D—adjusted for factor costs, (e.g., labor) public investment in R&D related to semiconductor manufacturing in the US lags that in Taiwan and Korea.

In addition to these two most fundamental challenges, other priority areas for improvement in the US include:

- 3 Industry clusters at scale
- 4 Semiconductor research networks
- 5 Continued access to world-class semiconductor R&D talent
- 6 Expansion of the US semiconductor manufacturing workforce.

This strategic challenge will require substantial commitment from private sector over multiple years, supported by comprehensive US public policy.

1. U.S. Innovation and Competition Act of 2021 (USICA), formerly known as the Endless Frontier Act



About This Report

To assess the current relative positions of different regions in advanced logic technology and potential strategic paths to achieving technology leadership in this arena, Intel commissioned Boston Consulting Group to conduct an independent study.

The work focused on answering two questions. (1) What has happened to US leadership in advanced logic technology? (2) What would it take to reestablish technology leadership in the US? BCG is wholly responsible for the analysis and conclusions that appear in this report.



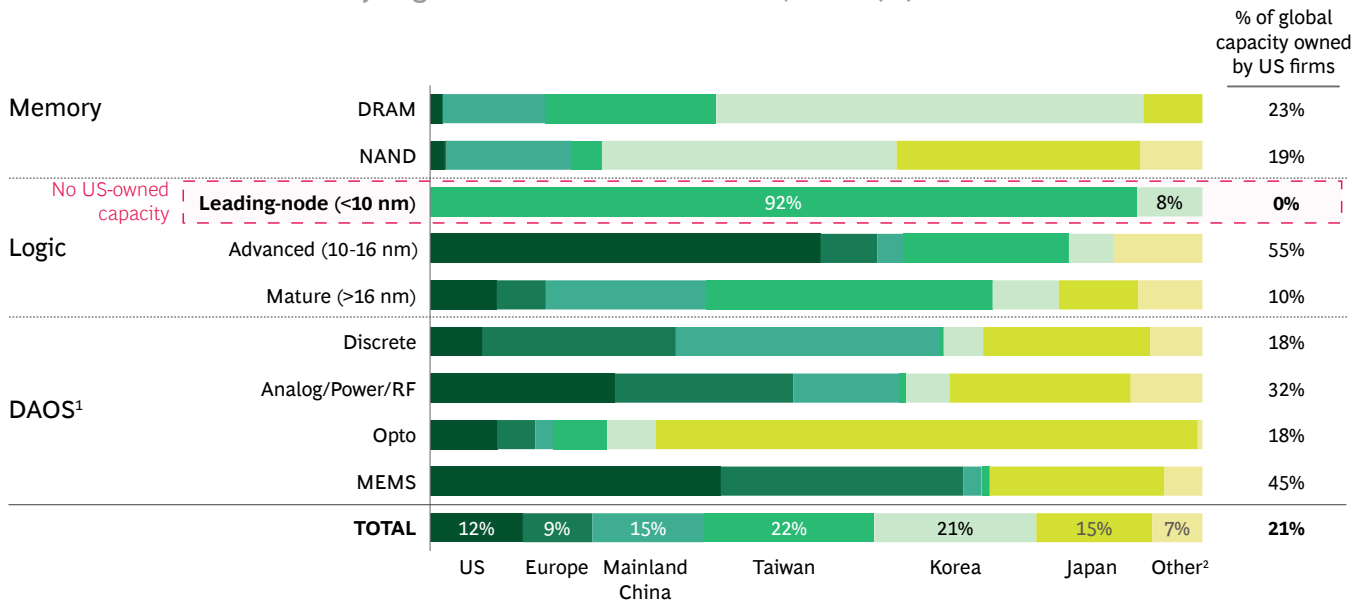
What happened to US leadership in advanced logic technology?

Semiconductors are the enabling technology of the digital age, and therefore are critical for the economic progress and national security of any developed economy. Semiconductors are also one of the four areas covered in the 100-Day Reviews mandated by President Biden under Executive Order 14017 focused on building resilient supply chains, revitalizing American manufacturing, and fostering broad-based growth. The report from this review, published in June 2021, establishes that “semiconductors are essential to the advanced technology powering economic, technological, and military competitiveness [in the US].”²

US firms have consistently accounted for 40% to 50% of total worldwide semiconductor sales in the last 30 years, while US OEMs account for about 33% of all semiconductor demand, making the US the clear global leader.³ This overall leadership position is built on strength in the activities across the semiconductor value chain that are most R&D intensive: electronic design automation (EDA) tools and core IP blocks, chip design, and manufacturing equipment. However, the US is heavily dependent on Asia for semiconductor manufacturing: just 12% of the global capacity for wafer fabrication and 2% of the capacity for

Exhibit 1—More than 90% of leading-node capacity, used to manufacture the most advanced logic chips is currently located in Taiwan

Global wafer fabrication by region based on fab location, 2019 (%)



1. Discrete, analog, optoelectronics and sensors 2. Other includes Israel, Singapore, and the rest of the world

Sources: BCG analysis with data from SEMI World Fab Database

packaging, assembly, and test is located in the US.⁴ In contrast, mainland China, Taiwan, South Korea, and Japan combined account for about 75% of the global capacity in wafer fabrication as well as packaging, assembly, and test.

The US led the industry in advanced logic technology and therefore leading-node manufacturing for more than four decades, pioneering major manufacturing technology developments such as the transition to strained silicon at 90 nm, to high-k metal gates at 45 nm, and to the FinFET transistor architecture at 22 nm, and was first to reach the 14 nm node in 2014. As Exhibit 1 shows, over 50% of the global installed capacity in the 16, 14, and 10 nm nodes—which were leading-nodes between 2014-2018 and are now referred to as advanced nodes—is located in the US.

Leadership in advanced logic technology requires a sustained investment in R&D and manufacturing facilities of over \$15 billion per year.⁵ This is the only way to maintain the relentless pace of innovation in

process technology that requires migration to smaller, more complex nodes, every two to three years—a regular cadence of technology improvement commonly referred to as “Moore’s Law.” With these extreme requirements for investment and expertise, the number of companies capable of manufacturing on leading nodes has shrunk to just three companies from more than 25 back in 2000, when the leading node was 130 nm. These three are Intel in the US, TSMC in Taiwan, and Samsung in South Korea.

TSMC and Samsung first challenged Intel in 2018 with the introduction of their new 7 nm leading node, before pulling ahead in ramping 5 nm node production in 2020. As a result, the broad trend of US reliance on non-US manufacturing capacity is most significant in leading nodes, which today are typically considered to be manufacturing nodes below 10 nm⁶. (See Exhibit 1.) Leading nodes are critical for manufacturing the most powerful advanced logic processors⁷ used in most sophisticated electronic devices—such as data centers, networking equipment, PCs, smartphones, smart “edge” devices with machine learning/

2. US White House, Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth, 100-Day Reviews under Executive Order 14017, June 2021

3. Semiconductor Industry Association (SIA), Factbook 2020, April 2020

4. BCG and Semiconductor Industry Association (SIA), Strengthening the Global Semiconductor Supply Chain in an Uncertain Era, April 2021

5. Average of estimated R&D for manufacturing and capital expenditure of TSMC and Intel in 2015-2020

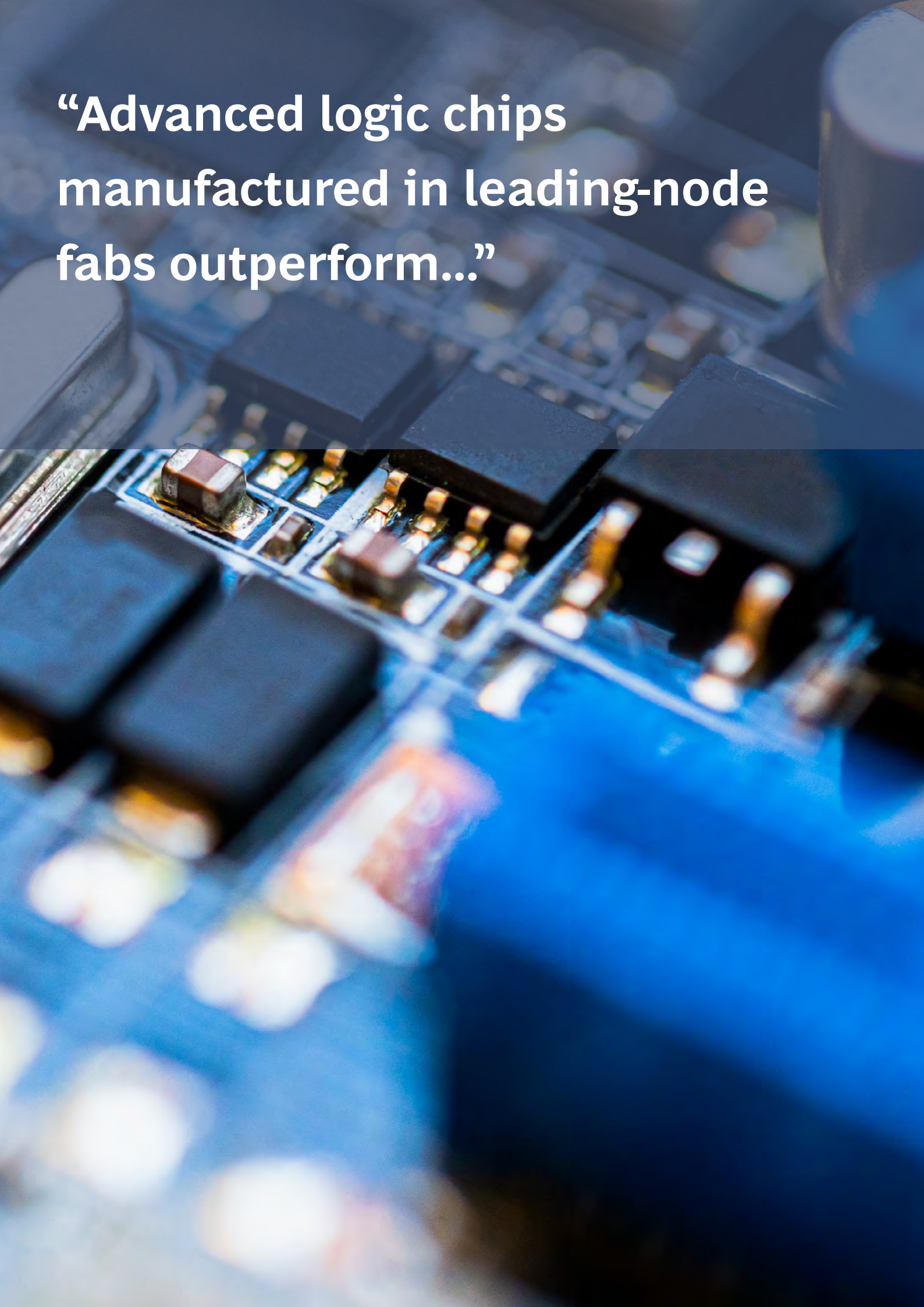
6. Leading node denominations in this report correspond to the typical industry definitions based on nanometers used by TSMC and Samsung and also consistent with the new Intel node denominations announced in July 2021. These node names should be understood as notional references: traditional nanometer-based process node naming stopped matching the actual gate-length metric in 1997. Further, the transistor density of Intel’s 10 nm node and TSMC’s 7 nm node are roughly comparable.

artificial intelligence (ML/AI) capabilities, and automotive advanced driver-assistance systems (ADAS). The high level of dependence on non-US semiconductor manufacturing capacity has been consistently identified as a major vulnerability by the US Department of Defense (DoD).⁸ Similarly, the recent White House report on the US semiconductor supply chain states, “with no leading-node semiconductor manufacturers in the United States or other members of the National Technology and Industrial Base, the DoD is currently unable to ensure its access to secure supply chains.”⁹ This exposes the US to risk of disruptions in access to advanced logic chips in the event of natural disaster, trade dispute, or military conflict in East Asia, as well as to other potential risks such as IP leakage or tampering-with of the chips that power sensitive critical infrastructure applications.

In addition to the supply chain risks associated with the geographic concentration of leading-node fab capacity, the White House report also acknowledges that secure access to state-of-the-art technology is needed to maintain a strategic advantage in “must-win technologies of the future” such as artificial intelligence and 5G, and to provide technical superiority for some military applications, including advanced communications and navigation systems and complex weapons systems such as those found in the F-35 Joint Strike Fighter. In fact, the US DoD Research & Engineering Enterprise unit has emphasized that “the lack of long-term availability of US-based trusted foundry services for [leading] and advanced nodes has become a concern and an impediment to DoD innovation.” In short, the US has lost its technology leadership in leading-node manufacturing.

7. For the purposes of this report, advanced logic chips includes microprocessors (MPUs), central processing units (CPUs), graphics processing units (GPUs), application processors (APs), field programmable gate arrays (FPGAs), and advanced processors designed for specific applications (ASICs)
8. Department of Defense, *Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency*, 2018; National Academies of Sciences, Engineering, and Medicine, *The Growing Threat to Air Force Mission-Critical Electronics: Lethality at Risk*, Unclassified Summary, 2019; Department of Defense, *Industrial Capabilities: Report to Congress*, 2020
9. US White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth*, 100-Day Reviews under Executive Order 14017, June 2021

**“Advanced logic chips
manufactured in leading-node
fabs outperform...”**



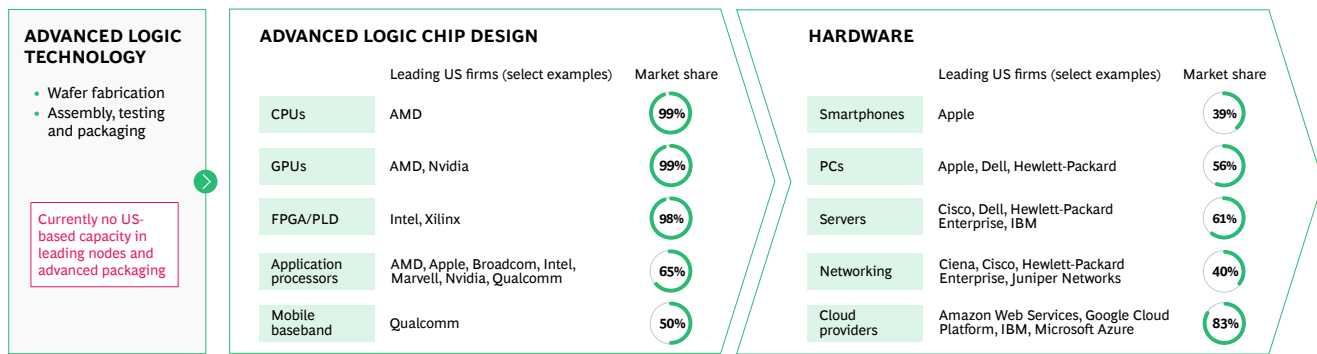


What would it take to reestablish technology leadership in the US?

Among all types of semiconductors, advanced logic chips are of particular strategic importance for the US. For example, seven of the ten technology focus areas designated in the US Innovation and Competition Act of 2021 (USICA)—a recent piece of legislation aimed at strengthening US leadership in critical technologies that was passed with wide bipartisan support by the Senate in June 2021—rely on advanced logic chips:¹⁰

- Artificial intelligence and machine learning
- High-performance computing and advanced computer hardware
- Quantum computing
- Robotics, automation, and advanced manufacturing
- Advanced communications technology
- Cybersecurity, data storage, and data management
- Biotechnology, medical technology, genomics, and synthetic biology

Exhibit 2—Leading US companies downstream in the electronics supply chain depend on access to advanced logic technology



Note: Market shares calculated in revenue terms for 2020. Sources: IDC; Gartner; BCG analysis

1. Including embedded MPUs, discrete application processors and certain ASICs
2. Including CSP and Enterprise equipment
3. Including IaaS and PaaS

Further, US defense modernization priorities also rely on advanced logic chips in areas such as AI, advanced communications, autonomous systems, cryptography, and cybersecurity.¹¹

The US is very well positioned both upstream and downstream in the advanced logic value chain. (See Exhibit 2.) US companies are global leaders in devices that are powered by advanced logic chips, with 40% to 60% market share in smartphones, PCs, servers, and networking hardware in 2020.¹² In the fast-growing cloud services market, which relies on massive computing power in large-scale data centers, the global share of US firms exceeds 80%. Another US firm, Tesla, is also the world’s leader in electric cars, which incorporate driver assistance features powered by advanced logic chips.

These advanced logic chips are also typically designed by US companies. In 2020, US semiconductor companies accounted for more than 95% of global sales of Central Processing Units (CPUs), Graphic Processing Units (GPUs), and Field Programmable Gate Arrays (FPGAs) in 2020.¹³ In Application Processors (APs)—including both standalone and those integrated with a baseband into a system-on-chip (SoC)—the combined global market share of US semiconductor design companies was over 50%.

However, although the vast majority of advanced logic chips are designed in the US, a significant portion (about

40% on a revenue basis) are manufactured in non-US leading-node fabs.

This is important because advanced logic chips manufactured in leading-node fabs outperform those made in advanced-node fabs. In the last 30 years, the performance of an advanced logic microprocessor manufactured on the leading node has increased at an annualized rate of over 25%, while the ratio of performance-per-watt of power consumption has also improved by over 10% per year.¹⁴ Looking forward, based on the roadmaps announced by TSMC, Samsung, and Intel, the ongoing migration from the 7/10 nm node introduced in 2017-2018, to the 3 nm node which is expected to launch in late 2022, is anticipated to continue to deliver major improvements in processor performance, power consumption, physical area, and cost. Therefore, advanced logic chips that are manufactured on the current leading nodes have a clear competitive advantage over those manufactured in older advanced nodes.

From a supply chain resilience perspective, the data in Exhibit 1 also shows that the potential risk of a severe supply disruption is much higher for leading-node logic chips than for other semiconductors that generally have a diversified geographic manufacturing footprint. Both Europe and Japan have the capacity and know-how in discrete, analog/mixed signal, MEMS sensors, and logic chips manufactured at mature nodes (above 16 nm); Japan, South Korea, and Singapore also have significant capacity

10. US Senate, S.1260 United States Innovation and Competition Act of 2021 (formerly known as Endless Frontier Act) — 117th Congress (2021-2022)

11. Department of Defense, National Defense Strategy of the United States of America, 2018; US White House, Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth, 100-Day Reviews under Executive Order 14017, June 2021.

12. Based on market data from IDC and Gartner for the respective device/service categories

13. Based on semiconductor market revenue data from Gartner

14. Based on analysis of data set obtained from Karl Rupp, 48 years of microprocessor trend data available here

in NAND memory and optoelectronics; and while in DRAM memory, South Korea accounts for over 50% of the global capacity, there is also significant capacity in Taiwan and Japan. In contrast, the US currently relies almost exclusively on Taiwan for leading-node manufacturing capacity.

In addition, many types of chips manufactured on mature nodes—microcontrollers or power management integrated circuits—often have longer product lifecycles and do not benefit as much from migration to smaller nodes as the most advanced processors. For example, currently, 32-bit microcontrollers are manufactured in a variety of nodes ranging from 28 nm to 130 nm, which have a more diversified geographic distribution. Furthermore, the US could potentially tap into the significant amount of domestic capacity that it still has in 80/90 nm or above¹⁵ as a back-up in case access to non-US manufacturing capacity was interrupted.

Therefore, building onshore leading-node capacity to manufacture advanced logic chips in the US is critical to strengthening the resilience of US supply chains. The provisions included in the CHIPS Act¹⁶ authorizing new federal incentives to attract global semiconductor manu-

facturing leaders to invest in building new fabs in the US are a significant step toward that end. While the CHIPS Act only has high-level guidelines for allocation of these investment incentives across specific fab projects, we expect more specific criteria to be issued by the Biden Administration. As an example of the potential impact of the CHIPS Act, we estimate that if about half of the \$52 billion of new US federal funds the Senate included in its USICA bill were assigned to leading-node manufacturing capacity,¹⁷ it could support the construction of five or six cost-competitive¹⁸ leading-node fabs, each with a capacity of 35,000 wafers per month, by 2030. This new capacity would likely be sufficient to cover the US need for advanced logic chips for *critical* applications—including aerospace and defense, communications networks, and infrastructure management—which represent about one quarter of relevant US consumption.

In parallel, the three companies currently capable of manufacturing at leading nodes—Intel, TSMC, and Samsung—have recently announced plans or begun construction on several new leading-node logic fabs in the US with the start of commercial production planned for 2024-2025.¹⁹

15. As shown on Exhibit 1, at the end of 2019 the US had about 9% of the total global capacity on the mature logic nodes above 16 nm—equivalent to approximately 16 fabs of 35,000 wafers per month. According to the SEMI World Fab Database, 70% of this US capacity corresponded to fabs of 80/90 nm or above

16. The CHIPS for America Act has been enacted as part of the fiscal 2021 National Defense Authorization Act (NDAA) in January 2021. Subsequently, the U.S. Innovation and Competition Act (USICA), passed by the US Senate in June 2021, has authorized \$52 billion of funding for the semiconductor research, design, and manufacturing initiatives in the CHIPS Act

17. This would be in line with some initial estimates of the “minimum viable US semiconductor manufacturing capacity” proposed by the Semiconductor Industry Association (SIA)

18. As discussed in the SIA’s report “Government Incentives and US Competitiveness in Semiconductor Manufacturing” advanced and leading-node logic fabs in Taiwan and Korea benefit from significant government incentives. Allocating 50% of the CHIPS act to advanced and leading-node logic fabs in the US would support building five or six fabs with cost structures comparable to Taiwan and Korea.



Exhibit 3—Beyond building some domestic leading-node capacity, creating strategic advantage for the US requires technology leadership



Building some leading-node fab capacity in the US

Global manufacturing leaders (either US- and/or foreign-owned) invest in building a few new < 10 nm fabs (e.g. 3-6 @35kwpm fabs) in the US to cover a portion of US semiconductor needs with domestic production

- ✓ Strengthens the US supply chain by reducing some of the current exposure to fabs concentrated in Taiwan and South Korea

Necessary, but not sufficient

Reestablishing the US as the global leader in advanced logic technology

US entities develop and own the technology IP/know-how to produce the most advanced logic chips ...

... enabling the expansion of US-based fab clusters to make the US a leading global manufacturer—including both wafer fabrication and packaging

- ✓ Removes US dependence on Taiwan and S. Korea
- ✓ Provides the US with strategic advantage in critical technology fields such as HPC, AI, etc.
- ✓ Reinforces US control over access by strategic competitors to semiconductor technology

Critical for US national security and economic progress

While incentivizing global players to build new leading-node logic fabs in the US is a necessary step in reducing current exposure to Taiwan and South Korea, achieving the more ambitious goal of regaining US technology leadership will require more because:

1) Strategic advantage in proprietary advanced logic technology requires localized R&D and IP leadership

Leading-node manufacturing relies on proprietary process technology developed through large investments in R&D sustained over time. As a reference, TSMC, the only one of the three companies with leading-node capabilities whose entire activity is focused on semiconductor manufacturing, currently invests \$3 billion to \$4 billion in R&D annually—over five times more than the companies that manufacture chips just on mature nodes. This number has been growing at an average 14% annual rate for the last ten years, reflecting the rapidly increasing cost of developing new leading nodes. IBS estimates that the cost of developing the process technology for a new leading-node has gone up by an average of 40% with each node introduced in the last two decades, from approximately \$100 million to \$140 million for the 180 nm node in 1999-2000 to the estimated \$4 billion to \$5 billion cost of the new 3 nm node planned for rollout starting in late 2022.

This R&D in proprietary process technology has typically

been conducted in the region of a company's headquarters. For example, since 2000, over 90% of all the patent filings related to manufacturing by TSMC, Samsung, and Intel referred to inventions originated in their respective home regions,²⁰ reflecting where most of their critical R&D in semiconductor manufacturing is conducted. So while having non-US-owned leading-node fabs in the US does increase supply assurance for US device makers, it will not by itself result in transfer of manufacturing technology or know-how to the US, let alone explicitly encourage increased R&D and proprietary IP development, effectively maintaining US dependence on other countries' technology in this critical area.

2) The expected impact of new leading-node fabs on the resilience of US supply chain is somewhat limited

The construction of five or six new fabs of 35,000 wafers per month (wpm) located in the US would amount to about 10% of global leading-node capacity expected to be operational by 2030—sufficient to cover around one quarter of US consumption. In addition, the announced US-based projects by TSMC (5 nm, with volume production start in 2024) and Samsung (5 nm, with production start in 2025) are expected to be one to two nodes behind the leading-node—by the time they start commercial production.²¹

19. Reuters, TSMC says has begun construction at its Arizona chip factory site, 1 June 2021; Taipei Times, TSMC unveils layout of Arizona fab, 3 June 2021; Austin American Statesman, Samsung wants \$1 billion tax incentive for new Austin plant that would create 1,800 jobs, 4 February 2021; Reuters, Samsung Electronics could begin construction of new U.S. chip plant in Q3, 17 May 2021; Intel press release announcing the 'IDM 2.0' strategy, 23 March 2021

20. Patent origin defined by the inventor address in the filing, irrespective of the country/countries where the patent was filed

Because of synergies within manufacturers' home regions as well as local interests, non-US companies have strong economic and non-economic incentives not to significantly scale their US footprints.

Illustrating the point on synergies, during the July 2021 earnings call, TSMC's Chairman Mark Liu stated that "Taiwan will continue to be the home base and center of R&D for TSMC. As the initial phase of volume production of a leading-node has to be in close proximity and closely coupled with R&D fab due to massive collaborative engineering activities, our leading node will continue to be ramped in Taiwan." In the same call with investment analysts, he also alluded to the cost differential of non-Taiwanese fabs relative to existing manufacturing operations in Taiwan. Both Samsung in South Korea and TSMC in Taiwan have large established semiconductor manufacturing clusters of three and eight times the size of existing US clusters, respectively. We estimate that building new capacity in an existing cluster can create savings of up to \$2 billion (5% to 7%) in the total cost of building and operating an leading-node fab vs. a greenfield site, on top of the cost advantages enjoyed in those locations due to local government incentives and factor costs (such as labor costs) relative to the US.

Further, a strong local semiconductor manufacturing footprint is also considered a matter of strategic importance by both Taiwan and South Korea. Taiwan's large semiconductor manufacturing footprint has been described as "a silicon shield" due to its geopolitical significance,²² and the Taiwanese government has reinforced its commitment to supporting the expansion of its local semiconductor manufacturing capabilities as a top priority going forward.²³ Similarly, in the May 2021 announcement of the national plan to invest \$450 billion in the semiconductor industry through 2030, the President of South Korea stated that the "... government will unite with companies to form a semiconductor powerhouse...we will support companies concretely."²⁴

In aggregate, these factors explain why nearly 90% of the capacity expansion by TSMC and Samsung since 2015 has been in their respective home countries and why TSMC's planned investment in the US over the next three years is less than 10% of the company's \$100 billion capital budget.²⁵

3) The US would have no export control of the advanced logic technology developed in Taiwan and Korea

The US has enacted several types of export controls, for example, restricting access by Chinese entities to advanced logic chips^{26,27} and restricting access by Russian entities to dual-use semiconductors.²⁸ However, such controls cannot be extended universally to chips or equipment that do not incorporate content of US origin.

In parallel, there is an increasing risk of intellectual property and know-how leakage associated with ongoing talent flows from Taiwan and South Korea to mainland China as it seeks to accelerate its push toward self-sufficiency. According to Taiwanese media reports, as of 2019 nearly 10% of Taiwan's total semiconductor R&D workforce (about 3,000 semiconductor engineers) had left for mainland China, including senior executives.^{29,30} Press reports also describe Chinese attempts to recruit Korean semiconductor manufacturing engineers with experience in plasma etching and yield management,³¹ and the Taiwanese government has now banned recruiting activities for jobs based in mainland China.³²

If the US wants to regain technology leadership, these three factors lay out why it will need to go beyond simply constructing some leading node fabs in the next few years. (See Exhibit 3.) This entails having locally developed and controlled process technology IP and know-how to manufacture the most advanced logic chips in the world, as well as enabling the expansion of US-based fab clusters to make the US a leading global manufacturer of advanced logic chips again—including both wafer fabrication and advanced packaging.

The next few years through 2030 present a real opportunity for the US to achieve this bolder aspiration. On the technology side, the industry roadmap for this decade focuses on continuing regular migration to smaller nodes. The move from the current leading node at 5 nm introduced in 2020 to 3 nm is expected to start in 2022. However, the transition to new leading nodes at 2 nm and below, expected to begin in 2024-2025, is not a linear progression of incremental optimization from today's manufacturing technology. Rather, it depends on a number of major technology breakthroughs. For example, the industry will mi-

21. TSMC introduced the 5 nm node in 2020 and has announced the start of volume manufacturing at 3 nm for the second half of 2022. Samsung introduced its first version of a 5 nm node (LPE) in late 2020 and has announced the introduction of its 3 nm node for 2022, with volume production for foundry customers expected in 2023

22. The term "silicon shield" was first introduced by Craig Addison, A 'Silicon Shield' Protects Taiwan From China, International Herald Tribune, 29 September 2000, and it is now widely used in media and academic coverage of the geopolitical issues around Taiwan

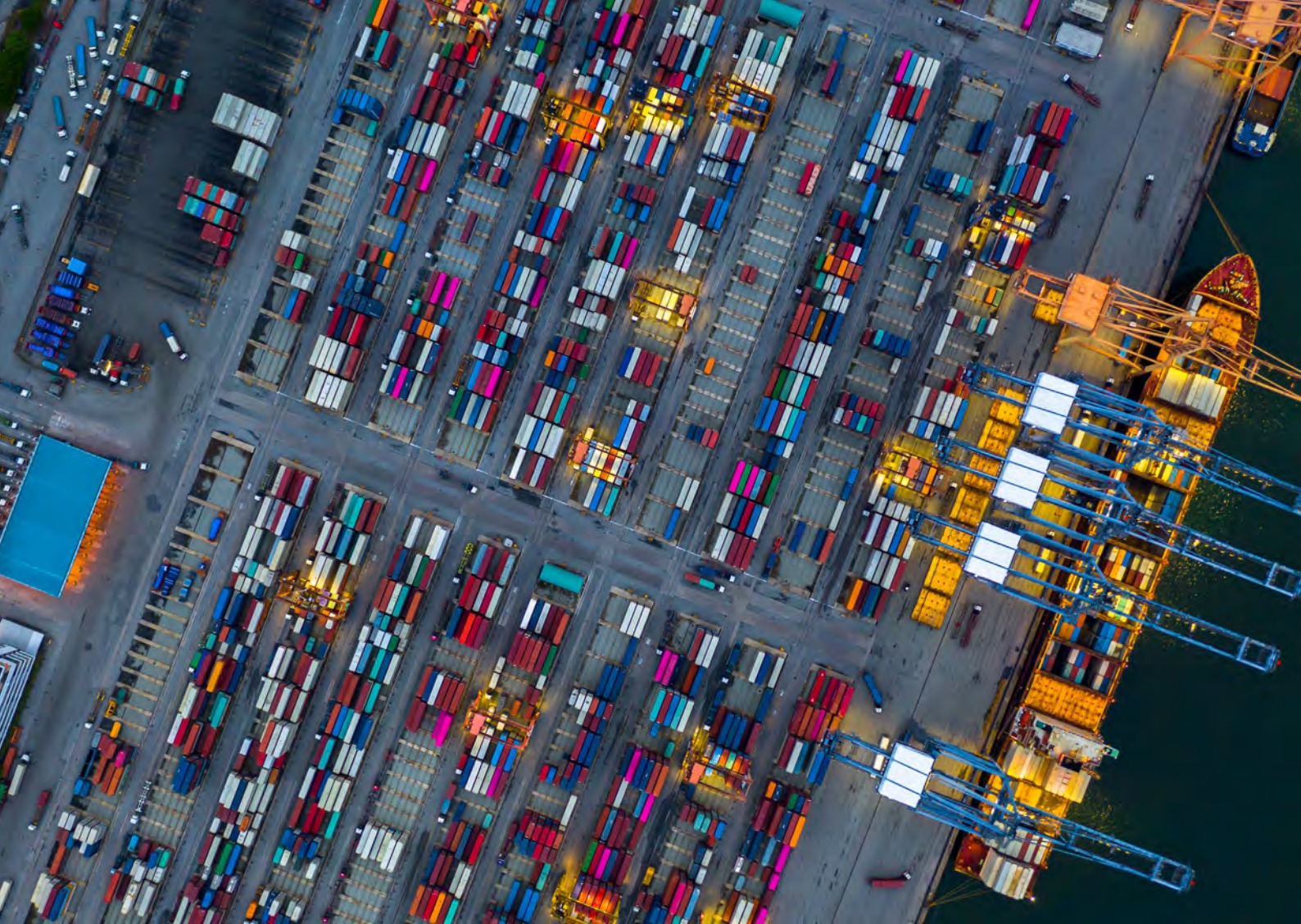
23. As an example, see Taiwan Today, President Tsai reiterates Taiwan's commitment to semiconductor industry, 25 September 2020; Reuters, Caught in China-U.S. trade war, Taiwan offers support to chipmakers, 23 September 2020

24. Nikkei Asia, South Korea plans to invest \$450bn to become chip 'powerhouse', 13 May 2021

25. TSMC Q2 2021 Earnings Call transcript, 15 July 2021, available through the company's website or Refinitive.

26. US Department of Commerce's Bureau of Industry and Security, Final Rule adding 77 entities to the Entity List, published on December 22, 2020

27. For a comprehensive review of US semiconductor export controls to China, see S. Khan, U.S. Semiconductor Exports to China: Current Policies and Trends, CSET Issue Brief, October 2020



grate from the FinFET transistor architecture introduced back in 2011 to the new GAA paradigm that makes vertical structures possible. Similar major technology leaps are required in architecture, materials, manufacturing process, and packaging to make manufacturing possible at nodes below 2 nm—these include the next generation of extreme ultraviolet lithography called High NA EUV,³³ backside power delivery, new memory, and low-resistance interconnect.

Most of these fundamental innovations are still in research and early development stages, which creates an opportunity for the US to double down on ongoing R&D efforts and leapfrog the current advanced logic technology leaders. Both TSMC and Samsung led in the introduction of ex-

treme ultraviolet (EUV) lithography technology in the first half of the past decade, which allowed them to be faster to ramp in the new 7 and 5 nm nodes. Similarly, the leaders in the next generation of leading nodes at 2 nm and below will be determined by today's R&D efforts.

At the same time, a large amount of new capacity needs to be built globally to meet expected future growth in demand for advanced logic chips. Based on the current range of analyst forecasts of the growth in the global sales of advanced logic chips, we estimate that at least 45 leading-node fabs of 35,000 wpm of capacity will have to be in production by 2030,³⁴ a major increase from the approximately six equivalent sub-10 nm fabs reported to be already operational in 2020.³⁵ (See Exhibit 4.)

28. <https://www.dlapiper.com/en/morocco/insights/publications/2021/03/united-states-imposes-significant-new-export-controls-and-sanctions-on-russia-and-china/>

29. Nikkei Asia, Taiwan loses 3,000 chip engineers to 'Made in China 2025', 3 December 2019

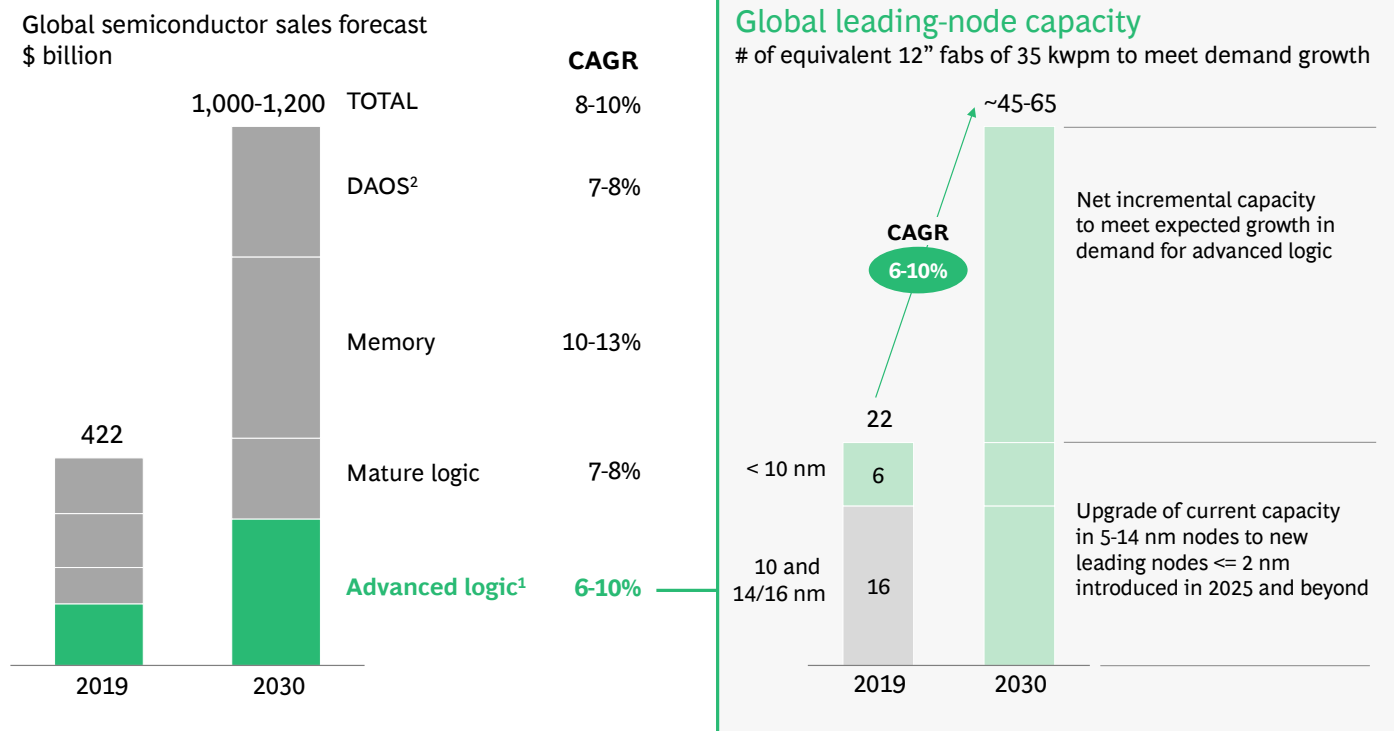
30. Nikkei Asia, China hires over 100 TSMC engineers in push for chip leadership, 12 August 2020

31. Business Korea, Chinese Companies Recruiting Korean Semiconductor Engineers, 24 August 2020

32. Bloomberg, Taiwan Probe Spurs Fears of China Poaching Top Chip Talent, 9 March 2021; Financial Times, Taiwan accuses Bitmain of poaching its top chip engineers, 10 March 2021; Nikkei Asia, Taiwan to invest \$300m in grad schools to stem chip brain drain, 16 July 2021.

33. For a comprehensive view of technology roadmaps of the semiconductor industry, see Institute of Electrical and Electronics Engineers (IEEE), International Roadmap for Devices and Systems (IRDS™), 2020 Edition

Exhibit 4—Expected demand growth provides a market opportunity this decade: at least 45 new 35 kwpm leading-node fabs must be built globally



Sources: BCG analysis based on data from Gartner, IBS, SEMI, IC Knowledge

1. Includes CPUs, GPUs, FPGAs, Application Processors, MPUs, mobile basebands and ~40% of ASICs 2. Discrete, Analog, Optoelectronics and Sensors/MEMS

These fabs will need to be commercially viable investments that can supply chips to global device OEMs, and invariably will be built in those locations around the world with the most attractive conditions.

Further, proprietary leading-node technology is developed through close collaboration of engineering teams in R&D and in the fabs. R&D without close collaboration from manufacturing teams cannot be effectively commercialized; hence the increasing focus on “lab-to-fab” Initiatives. And feedback from fab teams involved in first industrial deployment efforts is essential for R&D teams to further tweak process technology development. As the White House report on the 100-day review of the US semiconductor supply chain states, “When manufacturing heads offshore, innovation follows [...] ultimately, volume drives both innovation and operational learning; in the absence of the commercial volume, the United States will not be able to keep up [...] with the technology, in terms of quality, cost, or workforce.”³⁶

With the R&D and manufacturing incentives that the CHIPS Act can provide, the US has the opportunity to improve its semiconductor ecosystem so it can reestablish technology leadership and attract a significant portion of the new leading-node capacity. Domestic capacity and process technology development are strongly linked, and it is critical that incentives prioritize projects that can contribute on both fronts.

34. Estimates based on the 6% to 10% forecast range of long-term annual growth in advanced logic sales from industry analysts as of June 2021, assuming that almost all advanced logic manufacturing capacity in 2030 will be at 3 nm or below

35. SEMI World Fab Database, December 2020

36. US White House, Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth, 100-Day Reviews under Executive Order 14017, June 2021



Conclusion

Given how critical semiconductors are for economic competitiveness and national security, it makes perfect sense that reestablishing leadership in advanced logic technology is considered a national priority for the US.

Funding and subsequent deployment of CHIPS Act incentives, as well as completion of recently announced plans by Intel, TSMC, and Samsung to build leading-node fabs in the US, are necessary, and without qualification, positive first steps on that journey.

However, if the goal is to fully secure US technology leadership, provide the US with strategic advantage in critical technology fields, and reinforce the US's strategic control over access to semiconductor technology, the US will need to enable US-based control of leading-node process technology, additional manufacturing capacity, and complementary advanced packaging technology/capacity.

In our next report, we will work to define what potential US leadership ambition could look like, including specific technology milestones, an evaluation of 12 key success factors, and the joint investments required by the US government and private sector.

About the Authors



Raj Varadarajan is a managing director and senior partner in the firm's Dallas office and a core leader in BCG's Technology practice. You may contact him by email at varadarajan.raj@bcg.com.



Antonio Varas was a managing director and senior partner BCG's Silicon Valley office and global co-lead of the semiconductor practice until September 2021.



Ramiro Palma is a managing director and partner in the firm's Austin office, with a focus on the semiconductor industry. You may contact him by email at palma.ramiro@bcg.com.

Acknowledgment

This report would not have been possible without the contributions of our BCG colleagues Jesus Guardado, Sonali Chopra, Zainab Lasisi, Sohini Kar, and Yeonsoo Lee.

For Further Contact

If you would like to discuss this report, please contact the authors.

For information or permission to reprint, please contact BCG at permissions@bcg.com.

To find the latest BCG content and register to receive e-alerts on this topic or others, please visit bcg.com.

Follow Boston Consulting Group on Facebook and Twitter.

© Boston Consulting Group 2021. All rights reserved.

11/12

FSC stamp
goes here.

