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China's Progress in Semiconductor Manufacturing Equipment

Accelerants and Policy Implications

CSET Policy Brief



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Executive Summary

China has a chip problem. It depends entirely on the United States and U.S. allies for access to advanced commercial semiconductors, which underpin all modern technologies, from smartphones to fighter jets to artificial intelligence. China's current chip dependence allows the United States and its allies to control the export of advanced chips to Chinese state and private actors whose activities threaten human rights and international security. Chip dependence is also expensive: China currently depends on imports for most of the chips it consumes.

China has therefore prioritized indigenizing advanced semiconductor manufacturing equipment (SME), which chip factories require to make leading-edge chips. But indigenizing advanced SME will be hard since Chinese firms have serious weaknesses in almost all SME sub-sectors, especially photolithography, metrology, and inspection. Meanwhile, the top global SME firms—based in the United States, Japan, and the Netherlands—enjoy wide moats of intellectual property and world-class teams of engineers, making it exceptionally difficult for newcomers to the SME industry to catch up to the leading edge.

But for a country with China's resources and political will, catching up in SME is not impossible. Whether China manages to close this gap will depend on its access to five technological accelerants:

1. **Equipment components.** Building advanced SME often requires access to a range of complex components, which SME firms often buy from third party suppliers and then assemble into finished SME. Just as chipmakers cannot make chips without access to SME, firms cannot make SME without access to these specialized components (henceforth "SME components").
2. **Government subsidies.** China will likely provide billions of dollars in subsidies to its SME industry over the next five years. The volume of funding available to Chinese SME firms likely exceeds the fledgling industry's ability to efficiently absorb that funding.

3. **Explicit knowledge transfers.** Inspection and reverse engineering as well as intellectual property theft will help Chinese firms copy the advances made by top global SME firms.
4. **Tacit know-how transfers.** Approximately 1,100 Chinese nationals currently work at SME firms outside China. These workers return to China at low rates, but the few who do return bring valuable engineering know-how and often secure top jobs.
5. **Collaboration between Chinese SME firms and chip fabrication facilities (fabs).** Refining a product to achieve the high yield and throughput demanded by semiconductor manufacturers takes years and requires extensive testing and feedback from buyers. Chinese SME firms have struggled to find buyers willing to collaborate with them during this refinement process and to bring them revenue to accelerate their growth.

Reducing China's access to these accelerants will require a significant policy effort, but such an effort may be necessary to sustain China's chip dependence in the long term. To this end, we recommend the following policies, each aimed at reducing China's access to one or more of the five accelerants identified above.

The United States should continue screening foreign investments in SME firms and work with allies to harmonize investment screening practices. Harmonized investment screening policies will prevent Chinese firms from strategically acquiring companies possessing sensitive tacit and explicit knowledge and transferring that knowledge back to China.

The United States and its allies should more tightly control the export of technical data to China, but use deemed exports in a more targeted, limited way. Controls on technical data would reduce China's access to explicit knowledge. However, the United States should apply deemed export controls more sparingly by expanding exemptions and should process licenses more quickly. This would ensure foreign nationals stay in the United States and

contribute to U.S. industry, while taking a targeted approach to protecting against technology transfer.

To reduce China's access to critical components required to build advanced SME, the United States and its allies should impose export controls on these components. Examples include specialized light sources, laser amplifiers, and optics used to build extreme ultraviolet (EUV) and specialized light sources used to build argon fluoride immersion photolithography tools. China is already attempting to indigenize photolithography components, but robust controls would ensure Chinese firms cannot short-circuit this years-long and expensive process by importing these components instead.

The United States and its allies should export control advanced SME itself, especially any SME that China has yet to acquire.

These controls would deny China the ability to reverse-engineer SME, an important source of explicit knowledge. Controls on SME would also slow the development of advanced Chinese fabs, weakening China's semiconductor ecosystem.

The United States should prioritize assessment of SME component chokepoints, their value-add to SME, and vectors of technology transfer. These assessments would reveal additional policy options, including further SME components to target with export controls.

The United States should further study and promote transparency on Chinese government subsidies for SME. If such subsidies are found to be illegal under World Trade Organization (WTO) rules, the United States can consider challenging them. At a minimum, the United States and its allies can consider reducing export controls if China reduces its subsidy programs.

The United States and its allies should promote continued SME innovation through investments in R&D and workforce development. For now, leading SME firms based in the United States and allied countries enjoy an incumbency advantage: unlike Chinese SME firms, they have access to critical product feedback and revenues derived from sales to leading global semiconductor

fabs. Workforce and R&D investments would help accelerate the pace of SME innovation, allowing U.S. and allied firms to sustain their incumbency advantage in the years ahead.

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Introduction

China's semiconductor manufacturing equipment industry looks in 2020 much like Japan's SME industry of the mid-1970s. Like China today, Japan had a growing semiconductor industry and a large domestic market for finished chips, but its SME suppliers were weak or non-existent across almost every sub-sector.¹ Japan's sole strength in SME rested in assembly and packaging tools, where it benefited from lower labor costs, just as China does today.

Over 15 years, Japan's SME industry grew at an astonishing rate. By the early 1980s, Japanese firms together held almost 20 percent of the global SME market. From 1980 to 1990, the global SME market quadrupled in size, and Japanese firms' sales increased *eightfold* over the same period. By 1987, Japanese firms' technical capabilities rivaled or surpassed U.S. firms in most SME sub-sectors (Table 1). Meanwhile, sales for American firms merely doubled, leaving the United States with 45 percent of the global SME market, neck-and-neck with Japan's 43 percent.²

Table 1. 1987 assessment of U.S. vs. Japanese SME capabilities

	Japan lead	U.S.–Japan parity	U.S. lead
Photolithography		◀	
Electron-beam lithography			◀
X-ray lithography		◀	
Ion implanters			◀
Chemical vapor deposition		○	
Deposition, diffusion, other		○	
Energy-assisted processing	◀		
Assembly		○	
Packaging	◀		
Test	◀		

○ U.S. position maintaining ◀ U.S. position declining

Source: Interagency Working Group on Semiconductor Technology, 1987³

Many factors contributed to Japan’s success: government subsidies, engineering knowledge gained from blueprints and reverse-engineering of U.S. products, returnee talent trained at U.S. firms, and close collaboration—facilitated greatly by the Japanese government—between Japanese SME firms and Japan’s growing number of domestic chipmakers.⁴

Japan’s remarkable catch-up performance in the 1980s has had long-term effects. Japanese and American firms have lost some market share over the three intervening decades, especially to the Dutch photolithography firm ASML. But Japanese firms today still enjoy 31 percent of the \$77 billion global SME market, second only to the United States’ 41 percent.

China hopes to replicate Japan's success story—and the stakes are high. Starting in 2019, the United States and the Netherlands began to expand export controls on high-end SME, without which it is impossible to manufacture leading-edge computer chips.⁵ Deprived of access to advanced SME, China's \$145 billion domestic chip market⁶ will remain import-dependent for the foreseeable future—unless it can develop its advanced SME capabilities indigenously.

These new export controls have brought new urgency to China's long-term effort to develop an indigenous SME industry. For now, China has serious deficiencies in every sub-sector of SME except lower end segments such as assembly, packaging, and cleaning equipment. But China's industrial plans call for Chinese SME firms to supply at least 50 percent of the value of advanced SME purchased by Chinese chipmakers before 2025. And China hopes to develop a working extreme ultraviolet (EUV) photolithography machine—the SME industry's most expensive and sophisticated tool—by 2030. To further these goals, China's government plans to invest billions of dollars in SME firms over the coming decade.

Catching up in SME will be more difficult for China than it was for Japan in the 1980s, when the industry was young. In 1981, a single cutting-edge Micralign 500 lithography stepper sold for \$675,000—equivalent to \$2 million in 2020—and printed transistors with a precision measured in micrometers (around the diameter of a thread of a spider's web). Today's equivalents—the EUV machines made by ASML—sell at more than \$120 million per unit and print transistors with precision measured in nanometers (the length a fingernail grows in a few seconds). The industry has become highly consolidated, with five firms—Netherlands-based ASML, Japan-based Tokyo Electron, and U.S.-based Applied Materials, Lam Research, and KLA—capturing 65 percent of the global SME market. Across key subsectors, the number of firms operating at the leading edge has winnowed; for example, only ASML remains state-of-the-art in photolithography (Table 2).⁷ Leading SME firms have survived blistering competition and have amassed billions of dollars in capital and world-class engineering teams that benefit from decades of hands-on experience building

and operating ever-more complex machines. These firms have built up large moats of intellectual property: the top five firms obtaining over 2,000 U.S. patents in 2020, with high rates of patenting relative to other industries.⁸

But catch-up is not impossible. In the mid-1970s it must have seemed unlikely that Japanese firms would soon rival those of the United States. Yet within ten to fifteen years, Japan was second only to the United States in SME; a position it has held ever since. And China today has many of the key ingredients for catch-up that benefited Japan more than forty years ago. Like Japan in the 1970s, China is a major player in the assembly and packaging sub-sector of SME, and has a small but growing presence in most other sub-sectors. Like 1970s Tokyo, Beijing has set out ambitious development goals for its semiconductor industry and has dedicated tremendous resources to achieving them. China will likely spend billions of dollars on its SME industry over the next five years; and its technology transfer infrastructure, which employs more than 60,000 people, has made semiconductor progress a key priority. Perhaps most important, China's domestic demand for semiconductors is about 35 percent of the world's total⁹; and in 2016 it had eight times more STEM graduates than the United States and ten times more than Japan—gaps that will continue to grow in the coming years.¹⁰

This report assesses the gap between China's SME industry and the current leading edge; identifies and analyzes five key inputs to China's SME progress; and suggests policy levers for slowing that progress. It then takes stock of China's SME industry as a whole, assessing the technological gap between China's best SME firms and top global firms in the United States, Japan, and the Netherlands. The results reveal serious weaknesses across almost every sub-sector of SME, with particular shortcomings in the photolithography sub-sector. The paper then identifies five key factors that will dictate the rate of China's progress toward leading-edge SME. It closes with implications of this analysis for policymakers.

Chinese equipment firms lag behind the leading edge

Despite Beijing’s past efforts to catch up to the leading edge in the SME industry, there remains a wide technological gap between China’s SME capabilities and those of the top global SME firms. This section assesses the width of that gap across different SME sub-sectors.

It is hard to break into the SME industry. Even firms that have survived decades of blistering competition in the SME industry are today being winnowed away at the leading edge. Consider the photolithography sub-sector: already highly concentrated in 1990 with six leading companies, today just one company—ASML—leads the industry with a monopoly over the latest EUV technology (Table 2).

Table 2. Photolithography companies at introduction of each node¹¹

Type	Light source	Node (nm)	Year mass production	ASML (Netherlands)	Nikon (Japan)	Canon (Japan)	SVGL (U.S.)	Ultratech (U.S.)	Perkin Elmer (U.S.)
i-line	365 nm	800	1990						
		600	1994						
Krypton fluoride (KrF)	248 nm	350	1995						
		250	1997						
		180	1999						
		130	2001						
Argon fluoride (ArF)	193 nm	90	2004						
		65	2006						
ArF immersion (ArFi)	193 nm	45/40	2009						
		32/28	2011						
		22/20	2014						
		16/14	2015						
		10	2017						

		7	2018						
Extreme ultraviolet (EUV)	13.5 nm	5	2020						

Note: Green = Developed photolithography tools; Red = Did not develop photolithography tools.
Sources: Various.¹²

The handful of firms remaining at the leading edge in SME are almost exclusively headquartered in three countries—and China is not one of them. U.S., Dutch, and Japanese companies collectively enjoy between 80 and 95 percent market share in almost every sub-sector of the SME industry (see Box 1 for a breakdown of the tools that define the major sub-sectors of SME).¹³ China, by contrast, has less than 2 percent market share across almost all SME sub-sectors. Chinese firms have little to no capacity to build a range of critical SME, including tools for photolithography, wafer inspection, advanced ion implantation, atomic layer etching, and testing advanced logic chips.¹⁴ And most Chinese SME firms have virtually no sales outside of China, struggling to sell even to Chinese chipmakers. In all sub-sectors for which data exists, China’s localization rate is lower than 20 percent, meaning Chinese customers buy less than 20 percent of their SME (by value) from Chinese suppliers.¹⁵ Aggregating across sub-sectors, China has localized less than 8 percent of its \$14 billion annual domestic demand for SME.¹⁶

Box 1. Understanding semiconductor manufacturing equipment

Manufacturing modern computer chips is a highly complex process requiring a wide range of sophisticated semiconductor manufacturing equipment (**SME**). To begin, **wafer manufacturing** firms produce thin slices of pure silicon called wafers, which they sell to chip fabrication facilities, also known as “**fabs**.” Fabs then add dozens of layers of nanometer-scale circuitry on the surfaces of these wafers, using a wide range of tools in the process:

- The fabrication process begins with a **deposition** machine, which deposits a layer of material that then hardens on the surface of the wafer.

- A **resist processing** machine then applies a chemical called a photoresist on top of this hardened substrate.
- Next, a **photolithography** machine uses a system of mirrors, lenses, and lasers to project beams of light through a photomask—a window intricately patterned with shapes corresponding to transistors and other electronic components—onto the surface of the wafer. The parts of the photoresist that have been exposed through the photomask develop like a roll of film, while parts shadowed by the photomask do not, thus replicating the pattern described by the photomask on the surface of the wafer.
- **Etching** tools then chemically carve these projections into the hard substrate created during the initial deposition process. (Other times, instead of etching, atoms are embedded into the layer in a process called **ion implantation**.)
- Finally, the completed layer is flattened in a process called **chemical mechanical planarization (CMP)**, and the process starts over.¹⁷
- Throughout fabrication, **process control** tools inspect the wafer to ensure no errors, while **handling** tools transport the wafers and photomasks around the fab.

After fabrication, **testing** tools ensure the fabricated chip operates as intended. Finally, **assembly and packaging** tools cut dozens of individual chips out of each wafer and add protective and connective structures (called packaging) to the chips so that they can be integrated into products such as smartphones.

China does have two relative strengths in SME. First, like Japan in the 1970s, China's assembly and packaging equipment sub-sector benefits from relatively low labor costs: Chinese firms hold a considerable 22.9 percent of the global market (Table 3). Second, Chinese firms have produced sophisticated dry etchers, used for advanced logic, memory and packaging, since the early 2000s.¹⁸ Today, Chinese firm Advanced Micro-Fabrication Equipment (AMEC) advertises etching equipment for semiconductor manufacturing and packaging from 65 nm to 7 nm nodes, though much of its revenue derives from legacy nodes and larger feature sizes.¹⁹

These strengths should not be overstated, however. Assembly and packaging require less technological sophistication than other sub-

sectors and comprise just 4.9 percent of the SME market.²⁰ (And the chip production steps of assembly, test, and packaging account for only 10 percent of a chip's value.) In etch, China holds just 1.8 percent of the global market, despite recent advances, because AMEC's etch tools are not suitable for the most difficult parts of the lithography process.

Table 3. Revenue, market share and bottlenecks of leading Chinese SME firms by sub-sector

SME sub-sector	Leading Chinese firms	China's total revenue (\$M), 2019	China's % global market share, 2019	China's most important bottleneck ²¹
Assembly and Packaging	Hoson, Grand Tec	678	22.9%	No major gaps
Services	various	297	1.9%	-
Deposition	NAURA, Piotech	235	1.8%	Atomic layer deposition, rapid thermal processing
Etch	AMEC, NAURA	246	1.7%	Atomic layer etch
Process Control	RSIC, NAURA, Grand Tec	94	1.4%	Metrology and Inspection
Chemical mechanical planarization	Hwatsing	20	1.4%	CMP for advanced nodes
Test	AccoTEST, Hoson, JHT, Grand Tech, Shanghai Juno El, Changchuan	69	1.3%	Testing tools for advanced logic chips
Lithography	SMEE, Kingsemi	33	0.2%	EUV and ArF immersion photolithography
Ion Implanters	Kingstone Semi, CETC	-	0%	Ion implanters for advanced nodes
Wafer mfg., handling, marking	JSG, LanZhou, Beijing JingYi, SMEE	0	0%	Wafer manufacturing and handling
Total	-	1,672	2.2%	-

Source for revenues and market shares: VLSI Research²²

At the other end of the spectrum lies China's weakest sub-sector: lithography, which includes photolithography equipment and other

tools. The top Chinese photolithography firm, Shanghai Micro Electronics Equipment (SMEE), has existed for 18 years, but its most sophisticated tool operates at the 90 nm node, about eight generations (16 years) behind the currently leading 5 nm node.²³ And even SMEE's 90 nm tool is only a prototype, generating no sales.²⁴ Building a mass production-ready photolithography tool with low cost, low manufacturing error rates,²⁵ and high throughput can take years after initial prototyping, suggesting SMEE is even more than 16 years behind the leading edge.²⁶ Meanwhile, SMEE claims it will introduce a 28 nm ArF immersion tool in 2021 or 2022,²⁷ but this tool is expected to be unsuitable for mass production, with a throughput likely no more than one third that of commercially-viable counterparts. It may take SMEE additional years to refine the tool for commercial use.

Other parts of the photolithography industry have also posed problems for Chinese firms. SMEE struggles even to produce photolithography steppers: earlier-generation photolithography tools used both for making less advanced chips as well as for the packaging stage of chip production, in which finished wafers are turned into completed chips.²⁸ Meanwhile, China has no presence in the markets for electron-beam and laser lithography tools. These tools are necessary for creating the photomasks used in photolithography and for low-volume production of chips; and they are made only by U.S., Japanese, German, and Swedish firms.

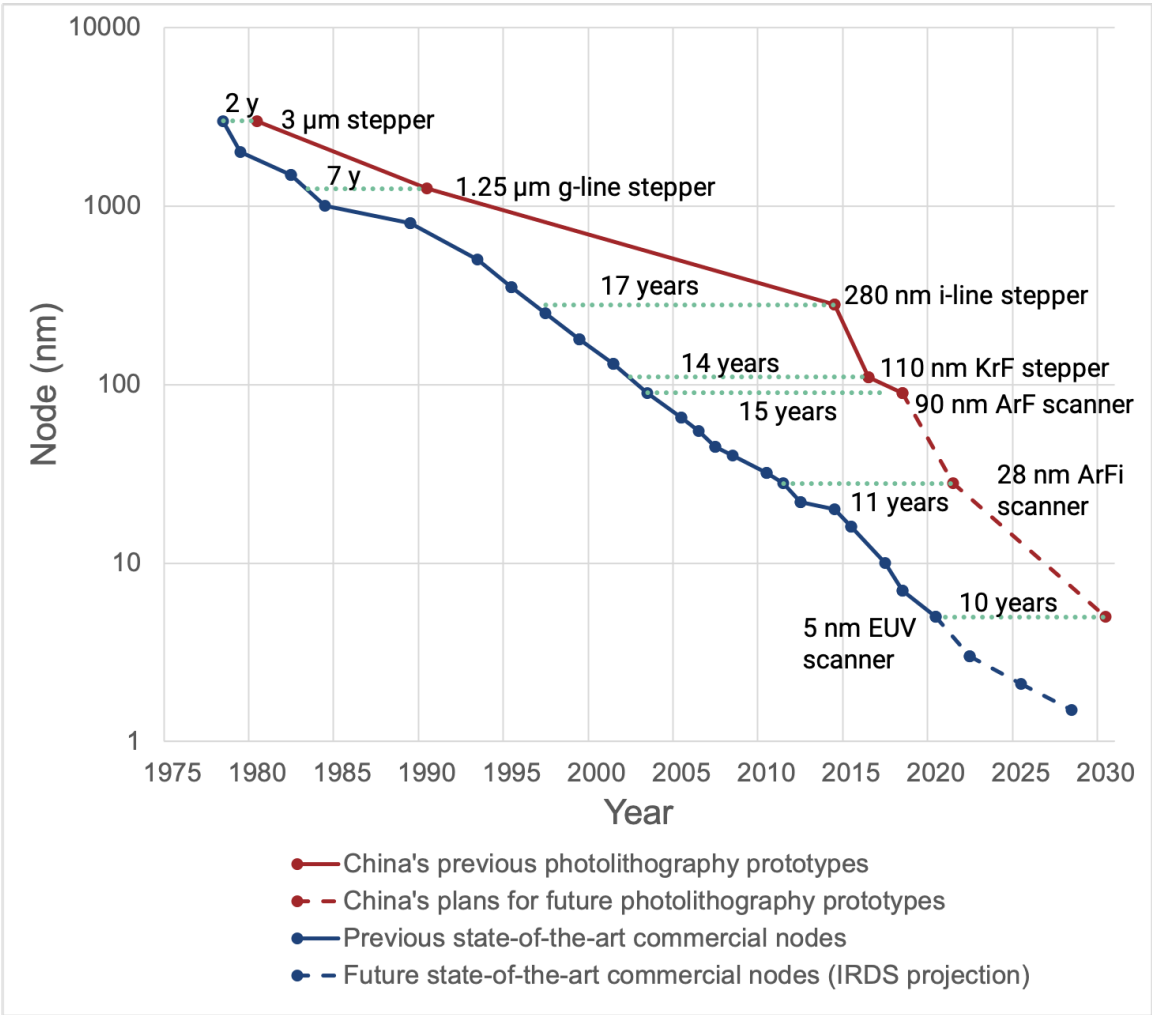
These severe weaknesses might surprise readers of Chinese news outlets, which tend to exaggerate China's capabilities in photolithography. In November 2018, for example, Chinese state media claimed that the Institute of Optoelectronics Technology of the Chinese Academy of Sciences developed a 22 nm photolithography tool.²⁹ The tool in question has low yield and throughput and is suitable for manufacturing chips in small, outdated wafers.³⁰ Moreover, given its technical parameters, this tool almost certainly cannot be used for making advanced chips.³¹

China's current capabilities in SME are far below the level targeted in its industrial plans. The "Technical Roadmap" accompanying Beijing's Made In China 2025 plan set forth a range of ambitious goals for SME localization, including 50 percent localization of 90–

32 nm process equipment by approximately 2018 and 50 percent localization for 90 nm photolithography by 2020.³² As of October 2020, localization remains below 10 percent across all SME sub-sectors except packaging and assembly; and China's leading photolithography firm SMEE has recorded no sales of its 90 nm tool.³³

These missed targets suggest that the goals in China's Technical Roadmap for EUV photolithography—which aim for China to indigenize EUV by 2030—are overly optimistic. The available evidence suggests that skepticism is warranted: In recent years, China has taken over a decade to prototype a given photolithography tool after that tool has first arrived on the global photolithography market (Figure 1). But in the photolithography sub-sector, it often takes years to turn a working prototype into a commercializable machine; indeed, Chinese firms have typically failed to transition from prototype to commercialization. Most recently, its flagship lithography firm SMEE has developed an ArF photolithography tool capable of operating at the 90 nm node 14 years after that node was first introduced. But whether these claims are valid depends heavily on what it means to “reach” a node. China has never managed to transition from a prototype to a machine that captured a significant percentage of the photolithography market.³⁴

Figure 1. The lag between Chinese photolithography prototypes and state-of-the-art commercial photolithography tools, 1978–2030



Sources: Various³⁵

While catching up in areas like photolithography appears difficult, experts disagree about precisely how long China might take to catch up to the leading edge in SME. In fall 2019, CSET asked five experts to estimate the time until Chinese firms become “internationally competitive” in three key SME sub-sectors. Experts gave a median estimate of ten to fifteen years, with a range of five to 25 years, for photolithography, and five to ten years, with a range of five to twenty years, for both deposition and etch.³⁶ See Appendix A for more survey details. (China may even fail altogether in building a competitive SME industry.)

This variation in response is justified. First, even if China does not reach the leading edge in deposition, etch, and photolithography by 2030, it still has tremendous room for growth at less advanced nodes.³⁷ Second, it remains unclear which actions China might take to hasten its progress, and which actions the United States and its allies might take to slow China’s progress. The remaining sections of this paper explore in greater detail the accelerants to China’s progress and how future policy actions might affect China’s access to these accelerants.

Accelerants to China’s progress

In order to catch up in the SME industry, Chinese firms will need access to some mixture of all of the following technological accelerants:

1. Extensive government subsidies.
2. Imports of critical SME components.
3. Explicit knowledge derived from blueprints, code, and other sources.
4. Tacit know-how transfers through recruitment of employees at leading global SME firms.
5. Collaboration between Chinese SME firms and semiconductor fabs.

Following is an assessment of China’s current access to each of these components and how each accelerant affects China’s progress in SME. Table 4 summarizes the current state of each of the five accelerants. The following subsections explain each of the five in greater detail.

Table 4. China’s access to key accelerants of SME progress

Input	Description	China’s current access
#1: Government subsidies	China’s government guidance funds—particularly the National Integrated Circuit Industry Investment	High. Chinese government investments in SME are not primarily limited by the volume of investment available, but by poor fund

	Fund—offer an ample, albeit often poorly allocated, source of funding to cash-strapped SME firms.	investment management and a dearth of SME firms able to absorb available funding.
#2: Equipment component imports	These components are needed to make SME. Like SME itself, SME components—such as EUV light sources—are often complex, expensive, and made by a single firm based in the United States or a U.S.-allied country. Chinese firms cannot build advanced SME without access to these components.	Moderate. The export of components specially designed for controlled SME, such as EUV tools, is currently controlled. (However, many other components may not be controlled.) Many component producers may also be subject to exclusive supply agreements with leading SME firms. Therefore, China is attempting to indigenize components, such as for photolithography tools.
#3: Explicit knowledge transfers	Engineering knowledge recorded in blueprints, patents, and data, or which can be inferred through close inspection and reverse-engineering of a finished product.	Moderate. China has a long-standing, large-scale, government-run program to transfer explicit technical knowledge of all kinds, including from top global SME firms, by legal, illegal, and extralegal means. ³⁸ These efforts may intensify over the coming decade.
#4: Tacit know-how transfers	Hard-to-articulate engineering knowledge that resides in the minds of experienced engineers rather than in written documents. This knowledge could be transmitted to Chinese firms via talent poached from top global SME companies.	Low. About 1,100 Chinese nationals currently work at top global SME firms outside China. Only a limited stock of returnee engineers—numbering only in the dozens—have joined Chinese SME firms. High-skilled Chinese engineers working abroad currently return to China at low rates, suggesting limited scope for tacit know-how transfers unless this changes. Chinese firms could also recruit engineers from Chinese sites at non-Chinese SME firms. China has also had some success recruiting engineers from Japan and South Korea.
#5: Collaboration between Chinese SME firms and fabs	It can take years to refine a prototyped SME into a tool that achieves sufficient yield and throughput to satisfy manufacturers. This refinement process benefits greatly from collaboration with fabs, which offer crucial product feedback.	Low. The world's leading fabs (Intel, Samsung, and TSMC), largely do not collaborate with Chinese SME firms, with few exceptions, such as TSMC's purchase of some of AMEC's etch equipment. Even Chinese fabs depend on non-Chinese SME.

Accelerant #1: Government subsidies

China's funding for its semiconductor industry, and SME firms specifically, flows through government-owned funds and enterprises. The most notable government guidance fund is the National Integrated Circuit Industry Investment Fund, also called the "Big Fund," which has thus far invested \$950 million in Chinese

SME firms. However, most subsidies are in the form of equity investments by local and central state-owned enterprises or government holding firms.³⁹ These investments represent critical, albeit often wasteful and poorly managed, subsidies for firms competing in the capital- and R&D-intensive SME industry.

The Big Fund is indeed big. In its first financing round in 2014, the fund raised 138.7 billion yuan (\$21.8 billion in 2014 USD) and had registered capital of 98.7 billion yuan (\$15.5 billion in 2014 USD).⁴⁰ By the end of 2017, the fund had made strategic investments in 67 projects, of which 24 were publicly traded companies.⁴¹ By August 2018, when the first investment phase concluded, it had invested in 70 companies.⁴² These are equity investments—not pure subsidies. But for firms operating in the capital-intensive semiconductor industry, a consistent source of billions of dollars in capital injections constitutes a major advantage.

The establishment of the Big Fund also spurred the creation of numerous sister funds injecting capital at the provincial and city levels.⁴³ By December 2017, the total size of Big Fund-driven sub-funds either proposed or established by various localities purportedly exceeded 300 billion yuan (about \$45 billion in 2017 USD).⁴⁴ An April 2018 estimate suggests that local funds in cities including Beijing, Shanghai, Shenzhen, Hubei, and Anhui amounted to more than 500 billion yuan (about \$80 billion in 2018 USD).⁴⁵ Chinese industry participants projected combined funding from national and local funds to reach 1 trillion yuan in 2020 (about \$150 billion in 2020 USD).⁴⁶

But the impressive scale of these investments comes with three important caveats. First, while local funds collectively dwarf the Big Fund, they tend to be wasteful and risk-averse.⁴⁷ Local governments often appoint inexperienced bureaucrats to manage their funds or impose constraints on these funds, limiting their effectiveness. Local funds also tend to avoid investing in smaller, newer companies, with only a minority of funds going toward venture capital investments.

Second, China's investments have overemphasized semiconductor fabrication at the expense of funding SME firms and innovative

startups. Table 5 breaks down Big Fund investments across the semiconductor supply chain in Big Fund Phase I. Counting early investments during phase II, the Big Fund has provided \$950 million in funding to China’s SME industry. Chinese analysts have argued that compared with etching equipment and thin film equipment, the localization rates of silicon wafer manufacturing equipment, lithography equipment, ion implanters, and measurement equipment are low, and that these technologies deserve greater fund support.⁴⁸ Investments from local funds and state-owned enterprises are more difficult to track, and likely account for most SME subsidies. However, some of these investments may likewise be skewed toward mature subsectors, as they are more fiscally constrained and less likely to make long-term bets on strategic technologies like SME.⁴⁹

Table 5. Big Fund Phase 1 investment across the semiconductor supply chain

Segment of supply chain	Percent of total investment	Estimated investment (USD)
Manufacturing	63	13.7 billion
Design	20	4.3 billion
Assembly, test, and packaging	10	2.1 billion
SME and materials	7	1.5 billion

Source: Various⁵⁰

Third, and perhaps most important, it remains uncertain how much funding China’s weakest SME firms are capable of absorbing. Wei Jun, vice president of the Big Fund, has noted the backwardness of Chinese materials and equipment companies is so profound that it could even be difficult to find suitable investment targets. State-run media admits that while the Big Fund has promoted Chinese SME companies like AMEC, NAURA, and National Silicon Industry Group, this has not yet allowed such companies to break into the higher end, nor significantly lowered dependence on SME imports.⁵¹ Firms like SMEE, which earns between 10 and 40 million

dollars in revenue per year, are unlikely to attract or effectively absorb billions of dollars in funding in the near term.⁵²

The second round of Big Fund investments (Box 2) appears to be targeting more strategically important parts of the semiconductor supply chain, including SME. For more mature SME firms capable of absorbing large investments, government funding appears to be ample.

Box 2: The second round of the Big Fund

News of the second round of the Big Fund approximately coincided with the annual government work report of 2018, in which promotion of the integrated circuit industry, for the first time, rose to the top of the list of Beijing's proposed economic policies.⁵³ Beijing has long viewed semiconductors as a strategic technology, but the last few years of trade tensions have driven home the extent of China's dependence on a range of technologies concentrated in the United States and allied countries. Big Fund president Ding Wenwu's public remarks on the second round of the Big Fund in 2018 highlighted the need to boost the semiconductor design, equipment, and materials industries "as much as possible."⁵⁴

By May 2020, the second round of the Big Fund had \$6.5 billion in registered capital.⁵⁵ \$2.2 billion of this capital will go to Semiconductor Manufacturing International Corporation (SMIC), China's leading semiconductor manufacturer; but other investments appear to be more evenly distributed across the supply chain, including smaller, emerging companies. In SME specifically, likely focus areas include etching machines, thin film equipment, and test and cleaning equipment, along with a focus on accelerating investment into core equipment such as lithography machines and chemical mechanical planarization equipment.⁵⁶

Access to capital is unlikely to be a key constraint for firms operating in the SME industry going forward. Indeed, when CSET asked experts in the semiconductor industry whether "a change in China's access to money and funding" would impact their estimates of China's timeline to becoming internationally competitive in SME, five out of seven respondents said "probably

not.”⁵⁷ Instead, Chinese SME firms will likely be bottlenecked in other areas, as discussed below.

Accelerant #2: Equipment component imports

Alongside SME itself, certain specialized SME components—parts used to make SME—present chokepoints underexploited by U.S. and allied export controls, likely because they are buried deep in the semiconductor supply chain. Consider:

- (1) Apple’s iPhone is made from a range of parts sourced from more than 200 companies from around the world—including advanced chips made by TSMC.
- (2) To build these chips, TSMC relies on hundreds of input technologies, including advanced SME. TSMC cannot make the most advanced iPhone chips without EUV photolithography tools provided by ASML, for example.
- (3) To produce SME such as EUV photolithography tools, firms like ASML are themselves dependent on specialized SME component manufacturers.

One option for slowing down China’s progress toward advanced SME is to export control the components required for making SME. These components, like SME itself, are often highly complex and developed only by a handful of firms. For example, EUV photolithography scanners, which are essential for manufacturing leading edge chips, incorporate a range of highly complex components manufactured exclusively by firms based in the United States and allied countries. Critical components of ASML’s EUV photolithography scanners include:⁵⁸

- Complex systems of mirrors sold only by German optics firm Zeiss.
- Laser amplifiers sold only by the German firm Trumpf.
- A light source provided only by Cymer, an American subsidiary of ASML.

While a few other firms could develop alternatives to these three EUV components, those firms also tend to locate in the United States and allied countries.⁵⁹ Argon fluoride immersion photolithography tools—sold only by ASML and Nikon—likewise rely on specialized components, including light sources provided only by Cymer and Gigaphoton. Further research could likely identify additional components required for manufacturing advanced SME: ASML alone relies on thousands of component suppliers to make its EUV photolithography tools.⁶⁰

China currently has variable access to SME components. The export of components “specially designed” for controlled SME—which include EUV tools—is currently controlled.⁶¹ Additionally, many component producers may be prevented from selling to China if they are bound by exclusive supply agreements with leading SME firms.⁶² On the other hand, unspecialized components or components specially designed for uncontrolled SME may not be controlled. Some Chinese analysts have argued that an inability to access key components of photolithography equipment is the single biggest reason China has fallen so far behind in this sub-sector.⁶³ In the meantime, China is attempting to indigenize components, especially for photolithography tools.

The risks of export controls may continue to drive China to indigenize SME components rather than import them where possible. However, China’s prospects for indigenizing SME would slow if the United States and its allies are willing to ensure export controls on the critical components required for assembling advanced SME and whether policymakers are able to identify additional critical SME components to target with export controls.

Accelerant #3: Explicit knowledge transfers

The engineering knowledge required for building complex SME can be divided into *explicit knowledge* and *tacit know-how*. Explicit knowledge refers to engineering knowledge that is recorded in blueprints, patents, and data, or which can be inferred through close inspection and reverse-engineering of a finished product. It is distinct from tacit know-how: hard-to-articulate engineering knowledge that resides in the minds of experienced engineers

rather than in written documents. This section explores the likelihood and consequences of China gaining access to explicit knowledge; the next focuses on tacit know-how transfers.

It appears likely that China will gain both lawful and unlawful access to some of the explicit knowledge required to build leading-edge SME. The most readily-accessible explicit—and legal—knowledge resides in patents or patent applications, which typically publish no later than 18 months after filing and include high-level blueprints for inventions. Typically, some but not all elements of an invention described in an active patent are also legally protected: Chinese firms can licitly build the unprotected elements immediately. Firms must wait twenty years to make legal use of the protected elements. But even expired patents contain some knowledge that remains relevant to building leading-edge systems. For example, ASML began to develop EUV in earnest during the early 2000s, meaning that some of its oldest EUV-relevant patents will begin to expire soon, giving Chinese firms unrestricted access to these innovations.

Another licit path to gaining explicit SME engineering knowledge is reverse-engineering equipment sold by top firms. This is exceptionally difficult and requires buying and then disassembling expensive equipment, likely destroying much of the equipment's value in the process. Nevertheless, reverse-engineering has played a role in various states' efforts to replicate American technologies, including China's effort to build a competitor to the F-22 fighter jet⁶⁴ and Japan's effort to catch up in the SME industry in the 1970s and 1980s.⁶⁵ Indeed, Japan's VLSI project, which yielded 1,000 patents between 1976 and 1979, spent between one third and one half of its funds to purchase advanced U.S. production equipment, much of which was simply dismantled and analyzed for reverse engineering.⁶⁶ Of course, the complexity of equipment has exponentially increased over the past four decades, making this strategy more difficult today.

China will also likely allow IP theft of proprietary blueprints and data from leading SME companies. This proprietary data contains knowledge that is often more detailed, product-specific, and valuable than what is publicly disclosed in patents. When China

prioritizes a given high technology, cases of IP theft involving Chinese nationals often follow. For example, jet engines have featured prominently in its Eleventh, Twelfth, and Thirteenth Five Year Plans.⁶⁷ In the past decade, the United States has accused a number of hackers and company insiders of working to steal intellectual property related to jet engine manufacturing from American firms.⁶⁸

Chinese actors have already stolen some SME-related explicit knowledge: former ASML employees allegedly stole documents containing trade secrets, possibly including source code, software, price strategies, and secret user manuals, and transferred them to Chinese companies. In 2019, ASML won an \$845 million judgment against the (now bankrupt) Chinese lithography firm XTAL for this misconduct.⁶⁹ Hacking groups with connections to mainland China have also targeted other parts of the semiconductor supply chain.⁷⁰

Given the risk of IP theft, SME firms have strong incentives to compartmentalize proprietary data and other forms of explicit engineering knowledge. SME firms make heavy use of non-disclosure agreements, cybersecurity measures, and other written rules governing information sharing to prevent explicit knowledge and tacit know-how diffusion.⁷¹ Many firms also refuse to open R&D sites in China due to concerns about weak IP protections and the potential for know-how transfers, while those that do open R&D sites take precautions such as sharing only low-end processes and technologies while keeping advanced functions outside of China.⁷² Indeed, ASML noted in the aftermath of the XTAL case that “there is no blueprint on the street where you can build a lithography machine.”⁷³

Accelerant #4: Tacit know-how transfers

As mentioned in the previous section, knowledge can transfer explicitly or tacitly. We focus here on tacit know-how: hard-won engineering knowledge, acquired through hands-on training and trial-and-error, which is near-impossible to write down and instead resides only in the minds of researchers and engineers. China’s progress in SME depends heavily in recruiting these experts. One approach is for China to convince many of the approximately 1,100

Chinese employees of top SME firms working outside of China to return to China (as this section will later discuss relative to Table 6).

SME has become extraordinarily difficult to copy. Even in the 1970s and 1980s, when SME was much simpler, Japanese firms seeking to catch up to the United States already relied much more on tacit rather than explicit knowledge transfers.⁷⁴ Decades later, SME is more complex than ever: building leading-edge tools requires innumerable design choices that depend on judgment calls, educated guesses, and years of hands-on experience.⁷⁵ Getting some of these choices right is difficult; but getting *all* of them right is necessary in order to achieve high yields.⁷⁶ Engineers learn to navigate these choices through extensive experimentation, manipulation, prototyping, testing, and refinement. And while the participation of a single star scientist can be helpful,⁷⁷ it takes a tightly integrated, highly experienced team to achieve consistent innovation.⁷⁸ It is nearly impossible to record or steal the engineering knowledge embedded in a highly productive team of SME developers.⁷⁹

This is the problem of tacit technological know-how. Consider the case of the U.S. F-22.⁸⁰ As combat aircraft have become more complex, from hundreds of parts in the 1930s to 300,000 in the 2010s, they have also grown in the tacit know-how required to develop them. China has struggled for years to produce its own competitor to the F-22 despite having benefited from extensive transfers of explicit knowledge via cyber operations, traditional industrial espionage, training from Russian aviation experts, and purchases of many critical components for reverse-engineering. China's J-20 Black Eagle, commissioned in 2017, remains inferior to the F-22, with a range of design flaws and an underpowered engine. The greatest hurdle for China in replicating the F-22 has not been a lack of blueprints or other explicit knowledge, but rather a lack of tacit and organizational know-how.⁸¹

The same is true of semiconductor manufacturing equipment, the most sophisticated of which can be comparable in complexity to an F-22.⁸² CSET asked seven semiconductor industry experts to rate the importance of four resources commonly thought to be important inputs to developing sophisticated SME. On average,

experts rated “talent with technical know-how” as the most important input; about as important as investment, access to blueprints, and access to SME for inspection combined. CSET also asked these seven experts whether a “change in China’s access to talent” would alter their estimates of China’s timeline to international competitiveness in SME. Four out of seven respondents said “Definitely yes,” and the remaining three said “Probably yes.” (See Appendix A for more details.)

In the case of EUV, the tacit know-how problem is especially serious. ASML’s equipment scans each photomask multiple times per second with 2-nm precision. A Chinese firm could purchase certain key EUV components such as light sources, optics, and laser amplifiers; but achieving the requisite level of mechanical precision requires developing and integrating a multitude of metrology and robotic systems—a tremendous challenge, which virtually requires the help of talent trained at either ASML or its Japanese competitor Nikon.

Chinese engineers working at top firms do not return to China at high rates, but the few who do can have significant impacts. Consider the case of Dr. Zhiyao Yin, co-founder of leading Chinese etch equipment manufacturer AMEC. Yin worked at companies such as Intel, Lam Research, and Applied Materials for two decades before returning to China to help advance domestic dielectric etching machines to near-world-leading levels.⁸³ Within a year of launching, AMEC announced the production of chemical vapor deposition and etch products. In a lawsuit filed in 2007, Applied Materials alleged that Yin, Aihua Chen, former general manager of Applied’s CVD product group and co-founder of AMEC, and 30 other former Applied Materials employees had misappropriated trade secrets and breached contracts.⁸⁴

Chinese firms also have other options for recruiting SME talent. One is to hire engineers from Chinese subsidiaries of non-Chinese SME firms—though this vector presents limited upside, as leading SME firms do not necessarily keep their most advanced operations in China. China could also recruit engineers from Japan and South Korea—a technique the country has already pursued with some success to build its semiconductor industry.

While an in-depth assessment of the potential for tacit know-how transfers to China is beyond the scope of this paper, we can get some sense of the risk by simply tallying the number of Chinese engineers currently employed outside China at top global SME firms using LinkedIn data.⁸⁵ Table 6 lists the number of workers with LinkedIn profiles who work for four of the five top SME firms by revenue.⁸⁶ Overall, 1.3 percent of these workers studied at Chinese universities, and most appear to be skilled technical workers. CSET estimates that all SME firms headquartered outside China employ a total of approximately 84,000 workers,⁸⁷ implying approximately 1,100 total Chinese employees of top SME firms working outside of China.

Table 6. Number of Chinese workers employed by top SME firms outside China

Company	Chinese workers employed outside China	Total workers	Percent Chinese workers employed outside China
Applied Materials	260	20,920	1.24%
KLA	123	7,111	1.73%
Lam Research	124	8,696	1.43%
ASML	260	20,700	1.26%
CSET extrapolation for all non-Chinese SME firms	1,100	84,000	1.3%

Source: CSET analysis using LinkedIn⁸⁸

The vast majority of high-skilled Chinese engineers working at top global semiconductor firms likely will not return to China for work unless immigration or export control rules force them to do so. Previous CSET analysis of NSF data shows that among Chinese Ph.D. students in semiconductor-relevant fields like electrical, electronics, and computer engineering, 90 percent tend to pursue jobs in the United States following graduation from American universities.⁸⁹ In the longer term, stay rates remain high: a 2018 report by the Oak Ridge Institute for Science and Education found that among Chinese science and engineering Ph.D. graduates from American universities, 86 percent remained in the United States ten years after graduation. While CSET has not conducted similar

analyses of the Netherlands and Japan, stay rates may be high in those countries as well.

Nevertheless, some workers do return home, and these returnees often secure top jobs at Chinese SME firms. For example, among the 274 employees with LinkedIn profiles at AMEC, China's leading supplier of etch tools, 32 have worked previously for top SME firm Applied Materials, an American company. AMEC has approximately 700 employees, so this likely underestimates the total number of Applied Materials alumni now working at AMEC. But these 32 employees are credentialed and well-placed within AMEC: among them are three vice presidents; two senior directors; one general manager; one global product manager; and one associate director.⁹⁰

Overall—in the absence of counterproductive policies that actively drive away Chinese talent currently employed by top global SME firms—returnee rates will likely remain low. Thus, China's SME firms, especially those further behind the cutting edge than AMEC, will struggle to gain access to the tacit know-how embodied in workers at top global firms. But a scenario where China recruits one thousand returnees with experience at top firms—with hundreds from ASML for photolithography—could have a large effect on China's SME progress.

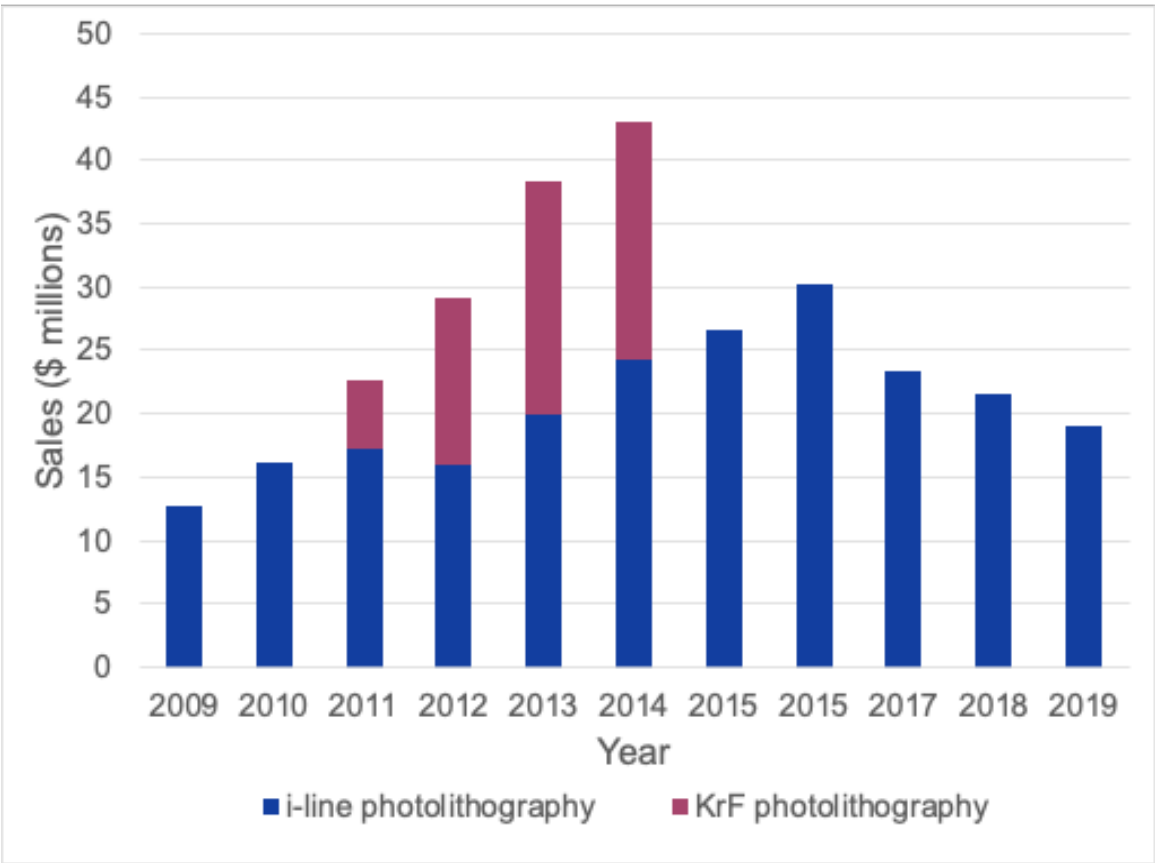
Accelerant #5: Collaboration between Chinese SME firms and fabs

Collaboration with top global semiconductor fabs would not only help Chinese SME firms catch up to the leading edge: it could allow them to keep up as the industry continues to innovate. While key components, subsidies, and explicit and tacit know-how can all help Chinese SME companies adapt innovations from top global firms more quickly, collaboration with top fabs (in combination with those accelerants) would help them keep pace with competitors. China would not only build a commercializable EUV photolithography tool on a shorter timeline; it would also be well-positioned to continue to close the gap in the years following.

In the SME industry, transforming a prototype into a commercially successful machine is a years-long process, requiring close collaboration between SME providers and the fabs they sell to.⁹¹ For example, ASML shipped its first EUV machine in 2010 and spent ten years working closely with chipmakers like TSMC, Intel, and Samsung to refine their EUV machines until they achieved satisfactory yields and throughput for mass production in 2020. As noted previously, China has a long history of developing prototypes of advanced photolithography equipment relatively quickly, but never achieving sufficient yield and volume for successful commercialization.

Even in cases where China has succeeded in commercializing a given tool, that success has often been temporary. For example, Figure 2 shows that in 2011, SMEE began earning revenue from a KrF stepper, more advanced than its workhorse i-line machine. But it discontinued shipments just three years later after struggling to attract sufficient enthusiasm from either domestic or foreign buyers. Meanwhile, revenue from its i-line steppers has declined considerably lately, from a peak of \$30.3 million in 2015 to \$19.1 million in 2019, and these steppers are used only for lower-end chip packaging, not chip fabrication. While such fluctuations are not uncommon in the competitive SME industry, they underscore the difference between building a tool that works in principle, and building one that satisfies manufacturers. The latter requires years of refinement and collaboration with fabs, and fabs are selective about which suppliers they collaborate with.⁹²

Figure 2. SMEE revenue by product type, 2009–2019



Source: VLSI Research

Chinese SME firms have struggled to gain substantial interest from top global fabs thus far.⁹³ In a notable exception, AMEC, China’s leading etch firm, has managed to secure Taiwan’s TSMC as a buyer. But while other leading chipmakers such as Intel, Micron, and Samsung have worked with Chinese firms to qualify their SME, particularly in search of better prices, they have yet to become serious customers. Most Chinese firms have struggled to sell their SME even to Chinese fabs, which are less advanced than global leaders. For example, SMIC—China’s top chipmaker, which remains multiple generations behind the leading edge—still largely buys its equipment from non-Chinese SME firms. China could use protectionist policies to force Chinese fabs to buy Chinese SME, but has not done so, given the risk of undermining China’s efforts to catch up to the leading edge in chip manufacturing.⁹⁴

Instead, China has recently begun a new strategy: R&D fabs aimed at qualifying Chinese SME for mass production. At least four such projects are announced or underway, with SMIC announcing one such facility in 2020.⁹⁵ This approach represents Chinese SME firms' second-best option if they cannot gain the business of the world's leading chipmakers.

Still, challenges remain for Chinese SME firms to gain substantial business. As discussed above, Chinese firms seeking to develop more advanced SME will likely run afoul of the extensive patents held by top global firms, which last for two decades from the time of filing. Chinese courts have been increasingly tough on patent infringement, accepting over four times as many cases in 2019 as they did in 2010 without discriminating against foreign plaintiffs.⁹⁶ And even if China were tempted to turn a blind eye to patent infringement by SMIC, the United States, Taiwan, and South Korea—home to the world's three leading-edge chipmakers—will not. This is a problem for two reasons. First, these firms lead the world in chip manufacturing, and can therefore offer uniquely valuable product feedback on the most sophisticated SME. Second, developing and building high-end SME is exceptionally R&D- and capital-intensive. Revenue from sales to top chipmakers will be critical if Chinese SME firms are to achieve financial independence from Chinese government subsidies.

The need for collaboration with fabs creates a Catch-22 for China's SME firms. The surest way to catch up to the leading edge in SME is to secure revenue and product feedback through sales to advanced fabs; but advanced fabs will not buy equipment from SME firms unless those firms are already at the leading edge. Thus far, most Chinese SME firms have not found a way out of this bind. China's best hope to qualify Chinese SME for mass production may be its new strategy of R&D fabs.

Recommendations

The previous section of this paper identified five accelerants that could substantially influence China's timeline for reaching the current cutting edge in SME: access to key components, government subsidies, explicit knowledge and tacit know-how,

and collaboration with advanced fabs located in the United States, South Korea, and Taiwan. The United States and its allies have policy options for affecting each of these accelerants. This section discusses seven options (not necessarily in order of importance), summarized in Table 7 according to how they affect each of the five accelerants to China’s SME progress.

Table 7. Recommendations for slowing China’s SME progress

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Screen investments in SME firms			✓	✓	
Impose export controls on SME technical data and deemed exports			✓	✓	
Impose export controls on equipment			✓		
Impose export controls on critical SME components		✓			
Prioritize assessment of SME component chokepoints and vectors of knowledge transfer		✓	✓	✓	
Study and promote transparency on China’s SME subsidies	✓				
Promote equipment innovation through R&D and workforce investments					✓

The subsections that follow each take a single row (in order) from Table 7 and explain what the policy recommendation in that row is and how it impacts the highlighted accelerant(s).

Screen investments in equipment firms

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Screen investments in SME firms			✓	✓	

To reduce the risk of explicit knowledge and tacit know-how transfers, the United States and its allies should better collaborate to block Chinese SME firms’ investments, joint ventures, and mergers and acquisitions targeting leading global SME firms. The United States screens sensitive investments in SME relatively carefully, but should continue improving its system to better identify any concerning transactions. But U.S. allies often have more lax investment screening policies that should be coordinated and strengthened.

The threat of technology transfer—particularly semiconductor-related transfers—has shaped the development of the modern U.S. investment screening regime since its establishment in 1988.⁹⁷ The Committee on Foreign Investment in the United States (CFIUS) is an interagency committee that reviews transactions by foreign entities to determine whether they raise national security concerns. The U.S. president blocks transactions on recommendations from CFIUS and has already done so for multiple cases involving SME firms.⁹⁸ CFIUS was first empowered to screen foreign investments largely in response to the rapid growth of Japan’s semiconductor industry and Japanese firm Fujitsu’s attempted acquisition of the American firm Fairchild Semiconductor.⁹⁹ In 2018, the Foreign Investment Risk Review Modernization Act (FIRRMA) broadened CFIUS’ powers and created mandatory notification requirements for investments involving critical technologies, including semiconductors and semiconductor manufacturing equipment, largely due to concerns about Chinese investments. As a result of these changes, U.S. investment screening policies are relatively strong.

The United States can improve these policies. First, it should ensure even all non-controlling Chinese investments in SME firms are captured. Second, it should avoid relying only on export control lists, which currently do not sufficiently capture advanced SME, and also would not include capture early-stage SME R&D for which export controls may be premature or unwarranted.¹⁰⁰

The United States should also engage its allies to ensure the implementation of strong and coordinated investment screening policies. Not all U.S. allies have developed their own investment screening bodies, and some use their powers much more actively than others.¹⁰¹ But both Japan and the Netherlands have recently updated or created investment screening policies, perhaps in part due to the passage of FIRRMA, which requires U.S. engagement with allies on investment screening.¹⁰² The CHIPS for America Act, included in the National Defense Authorization Act for Fiscal Year 2021, includes additional provisions to promote harmonized investment screening for semiconductors.¹⁰³ Still, allied measures have been insufficient. For example, since mid-2019, Chinese investors announced or were reportedly in talks for planned acquisitions of controlling stakes—worth \$125 million—in five Japanese firms selling semiconductor technologies, three of which sell SME.¹⁰⁴ Therefore, the United States should continue engaging allies and incentivize them to harmonize their investment screening policies, such as by expediting CFIUS investment screening for firms and individuals based in allied countries.¹⁰⁵

Impose export controls on equipment and its inputs

We recommend three forms of export controls below, each with complementary strengths:

1. Multilateral export controls on **equipment technical data and deemed exports** would control the transfer of know-how, both in the form of technical data and tacit know-how acquired by employees.
2. Multilateral export controls on **critical equipment components**—such as mirrors, light sources, and laser

amplifiers used to make EUV photolithography tools—would raise barriers to Chinese firms assembling SME.

3. Multilateral export controls on **SME** itself would reduce the risk of reverse engineering.

Equipment technical data and deemed exports

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Impose multilateral export controls on SME technical data and deemed exports			✓	✓	

The United States and its allies should more tightly control the export of technical data for key SME to prevent transferring engineering knowledge to China. However, the United States should more narrowly tailor deemed export controls—applying exemptions where possible and processing licenses more quickly. These policies would balance the benefits of ensuring foreign nationals stay in the United States and contribute to U.S. industry against the risks of technology transfer.

The differences between these two types of controls is subtle but important: whereas data controls would prohibit any individual from bringing technical knowledge back to China, deemed exports can prohibit *only* foreign nationals from working at SME firms outside their home country that could impart controlled technical knowledge.

Export controls on technical data have the advantage of applying to any individual, regardless of nationality, but the disadvantage of being difficult to enforce. These controls prevent only the export—not the acquisition—of technical data. It is difficult to detect when an individual worker has transferred knowledge to China. Even when such transfers are detected, China may refuse to extradite the individuals involved.¹⁰⁶ Still, these controls can be effective, and carry fewer risks than deemed export controls, so should be applied to critical advanced SME that China cannot produce.¹⁰⁷ One

particular acute risk is that non-Chinese producers can aid the development of China's photolithography industry by transferring currently uncontrolled technical data relating to photolithography tools that are less advanced than EUV tools, such as argon fluoride immersion photolithography tools.¹⁰⁸

Deemed exports have the advantage of preventing workers from acquiring technical data in the first place, but they could also have adverse effects depending on how they are applied. As noted previously in this paper, transfers of tacit know-how are a critical factor determining the rate of China's progress. Deemed exports target precisely these knowledge transfers: under U.S. law, a deemed export occurs when a foreign national acquires controlled technical data or source code, even if they are in the United States at the time. Accordingly, deemed export controls can prevent foreign nationals from accessing controlled technical data or source code while working for U.S. companies.

However, deemed export controls should be as narrowly tailored as possible to reduce technology transfer without deterring foreign nationals from working in U.S. industry. Deemed export license investigations are somewhat redundant with existing visa vetting processes. And broad deemed export controls would conflict with the U.S. technology sector's cosmopolitan values. Therefore, exemptions should be introduced where possible. One option is to grant general licenses to U.S. employers that institute sufficient security measures. Additionally, if policymakers expand controls to new SME, they should exempt experienced foreign nationals employed at U.S. SME firms from related deemed export controls, which may cause experienced Chinese engineers to leave when they would otherwise stay in the United States.¹⁰⁹ Finally, deemed export controls could focus on advanced SME that China has not yet acquired, such as EUV tools.¹¹⁰

Even well-targeted deemed export controls can be harmful if the U.S. Commerce Department lacks sufficient resources to process licenses quickly. In 2019, deemed export licensing delays reached nearly seven weeks on average for Chinese nationals with some delays as high as eight months. These delays can become de facto denials.¹¹¹

Critical equipment components

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Impose multilateral export controls on critical SME components		✓			

The United States and its allies should ensure that export controls cover critical, specialized components needed to produce advanced SME. This would serve as an insurance policy to prevent China from short circuiting its efforts to build SME by assembling imported components. Instead, China would be forced to indigenize these components before indigenizing SME, as it is currently attempting to do for photolithography tools. Like SME itself, many of the component parts of SME are built exclusively by firms in the United States and allied countries. This paper has previously noted that ASML’s EUV photolithography machines use mirrors sourced from German optics firm Carl Zeiss, laser amplifiers from Trumpf, a German equipment maker, and light sources from Cymer, an American firm. Each of these technologies is highly sophisticated and would take time for a Chinese competitor to replicate.

The effectiveness of export controls on components will depend on implementation. In general, multilateral or plurilateral controls will be more effective. For example, if the United States enforces export controls on optics but Japan refuses to follow suit, Japanese firm Gigaphoton could plausibly fill the void by developing EUV optics technology. Controls must also be enforced with a presumptive denial of export licenses for any end-use in Chinese SME. Licensing officers in the United States and allied countries typically approve export licenses for most semiconductor technologies, undercutting the effectiveness of controls.¹¹²

Additionally, while “specially designed” components for controlled SME—which include EUV tools—are currently controlled,¹¹³ the United States and its allies should interpret these controls to cover

EUV light sources, laser amplifiers, and optics. They should also further study whether additional controls are merited on components that are currently uncontrolled, which may include unspecialized components or components specially designed for uncontrolled SME.

The United and its allies can also consider end-user controls applied to Chinese SME firms. Military end-user export controls potentially already apply to AMEC.¹¹⁴

One risk of these controls is if China succeeds in indigenizing controlled components it would otherwise have imported and Chinese SME firms incorporate these components and gain market share. In this scenario, non-Chinese component suppliers could suffer sales losses, harming their ability to reinvest profits to sustain their competitiveness. Controls on components will work best if they are difficult for China to indigenize or if U.S. and allied SME firms can continue to outcompete Chinese SME firms in the Chinese market, despite the latter’s access to indigenous components.

Equipment

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Impose multilateral export controls on equipment			✓		

The United States and its allies should coordinate export controls on advanced, linchpin SME **that China has not already developed or imported** to reduce the risk of Chinese SME firms reverse-engineering advanced SME. Additional controls on linchpin SME that Chinese firms have already acquired could be desirable as well, as they will slow China’s progress toward the leading edge in chip manufacturing, although they will do less to reduce the transfer of explicit SME knowledge. Countries participating in multilateral or plurilateral export controls should also apply controls extraterritorially to prevent firms headquartered in member

countries from moving production to countries not applying export controls.¹¹⁵

Export controls often spur the indigenization of strategically important technologies within countries targeted by controls, while harming the competitiveness of U.S. firms. For example, export controls on U.S. satellite technologies likely contributed to the decline of the U.S. space industrial base and the rise of globally-competitive space industries in other countries.¹¹⁶

If carefully-targeted, however, export controls can slow indigenization. The previous section of this paper argued that access to finished SME for inspection and reverse-engineering is a source of explicit knowledge. While it is exceptionally difficult to reverse-engineer the most complex modern SME, careful inspection of leading-edge devices would likely help, just as it likely helped China to (imperfectly) replicate American F-22.¹¹⁷ Thus, for EUV photolithography machines and other advanced SME China has never acquired, export controls would cut off a source of explicit knowledge, hindering China's reverse-engineering efforts.

By contrast, export controls on SME that China has already acquired in significant quantities have more ambiguous effects. On one hand, such controls would slow the creation or development of China's leading-edge chipmakers, depriving Chinese SME firms from collaboration and revenue sources. On the other hand, controls may bind Chinese SME firms and Chinese chipmakers closer together, perhaps accelerating the formers' progress in the long term. The case of Japan elucidates this risk. In the 1970s, Japan's protectionist policies ensured Japanese fabs would buy tools from Japanese SME suppliers. This gambit paid off; in the early 1980s, Japanese chipmakers beat U.S. chipmakers to the market with 64-bit DRAM memory chips, expanding both the Japanese memory chip and SME industries.¹¹⁸

Even if China already has access to a given SME for reverse-engineering, export controls on that SME may still be desirable due to their effects on China's chip manufacturing capabilities. As argued in other CSET research,¹¹⁹ export controls on certain advanced SME required for advanced chip manufacturing—such as

tools for ion implantation, atomic layer etch, and EUV and ArF immersion photolithography—would slow the progress of China’s leading chipmakers. Indeed, one goal of slowing China’s SME indigenization is to ensure that export controls on SME remain effective in slowing China’s chipmaking progress, thereby sustaining China’s import dependence on the United States, South Korea, and Taiwan for leading-edge chips.

Prioritize assessment of SME component chokepoints and vectors of technology transfer

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Prioritize assessment of SME component chokepoints and vectors of knowledge transfer		✓	✓	✓	

As a first step toward controlling China’s access to critical SME components and SME-related technology transfers, the U.S. government should prioritize the assessment of SME component chokepoints, their value-add to finished SME, and vectors of SME technology transfers to China. Intelligence alone will do little to slow China’s SME indigenization efforts, but without a clear understanding of which SME components represent the most promising chokepoints, how much value these components contribute to finished SME, and which vectors of knowledge transfer are most problematic, policies aimed at slowing China’s indigenization of SME could be ineffective or even counterproductive.

Good intelligence is critical for formulating export controls that impact China’s efforts to indigenize advanced SME. As noted previously, export controls on certain SME components—inputs SME firms use to assemble finished SME—could help slow China’s indigenization of advanced SME. But identifying which components offer the most promising targets, and whether international cooperation on new export controls is necessary, is a

difficult analytic task, as SME firms may not disclose where they source their components from. Identifying firms that could offer substitutes for export-controlled products is a further challenge. Knowing how much value such components add to finished SME is also critical. For example, ASML's EUV tools incorporate U.S.-origin technology (particularly EUV light sources), whose value-add would better inform the appropriate "de minimis" threshold for potential extraterritorial U.S. export controls on shipments of EUV tools from the Netherlands to China. (Under the de minimis rule, U.S. export controls apply to exports from one foreign country to another if an item includes a threshold percentage of U.S.-origin content controlled in the receiving foreign country.) All of this information is critical if export controls on SME components are to be effective.¹²⁰

The same reasoning applies to policy efforts to reduce flows of SME-related explicit and tacit knowledge to China: a good understanding of China's transfer efforts will help the United States formulate effective counter-transfer policies. To reduce the frequency and severity of SME IP theft, the United States and its allies would benefit from first understanding which technologies within the SME industry are most likely to be targeted by Chinese firms.

We offer three potential ways the U.S. intelligence community could prioritize assessment of SME components and vectors of technology transfer. First, the assessment of SME components and vectors of technology transfer should be prioritized in the National Intelligence Priorities Framework (NIPF). The NIPF informs National Intelligence Program planning, programming, and budgeting activities and the allocation of collection and analytic resources and can be updated on an ad hoc basis to reflect emerging priority issues. The NIPF should be updated to reflect the importance of the SME industry to China's overall effort to gain semiconductor independence.

A second option for improving on current monitoring efforts is to establish an open-source National S&T Analysis Center.¹²¹ Relative to the United States, China currently has many more resources devoted to the collection of open-source intelligence (OSINT) on

global S&T developments. The United States intelligence community has historically focused on classified analyses of military affairs and technical collection, while marginalizing OSINT.¹²² However, open-source analysis is especially useful for monitoring fast-moving developments in advanced technologies.

However, intelligence-gathering efforts will do little good unless policymakers act to slow China’s SME indigenization efforts. The intelligence community should therefore communicate findings to the export control agencies;¹²³ U.S. agencies responsible for cyber defense; and the Committee on Foreign Investment in the United States, which screens foreign investments in U.S. firms. Therefore, a final option to avoid this step is for the Bureau of Industry and Security to receive increased resources to perform aspects of this analysis on its own. Additional expertise within BIS—such as SME engineers and market analysts—could also improve BIS’s to more quickly adapt controls, including export licensing processing, to the fast pace of technological change in SME.

Study and promote transparency on equipment subsidies

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Consider challenging China’s SME subsidies	✓				

As Beijing increases SME subsidies in the second round of the Big Fund and other funds do the same, the United States and its allies should carefully assess them and continue to press China for transparency on their size and nature. One study found that Beijing’s state subsidies to Chinese chipmakers reach as high as about 40 percent of firm revenues.¹²⁴ China may eventually apply comparably large subsidies to its SME firms, which will likely struggle to reach the current leading edge without extensive financial support from Beijing.

Although China is highly unlikely to drop its subsidy program under any circumstances, the United States has multiple options to

attempt to achieve this outcome. First, the United States can consider challenging these subsidies at the World Trade Organization. However, there are risks to this approach: such a challenge may not succeed if there is insufficient evidence to prove that the subsidies are illegal under WTO rules, could take years to resolve, could provoke retaliation by China, and may fail to garner support from allies. A better approach may be for the United States to launch negotiations with China, with reduced export controls as a bargaining chip.

Promote equipment innovation through R&D and workforce investments

Accelerants	Government subsidies	Imports of SME components	Explicit knowledge transfers	Tacit know-how transfers	Collaboration between Chinese SME firms and fabs
Policies					
Promote equipment innovation through R&D and workforce investments					✓

The United States must strengthen its funding for R&D, as well as its domestic workforce, in order to preserve its leadership position in the SME industry. As argued in the previous section of this paper, China’s SME firms currently face a Catch-22 as leading SME firms in the United States, Japan, and the Netherlands are not just better-resourced—they also benefit from collaboration with leading-edge fabs, which provide invaluable product feedback throughout the process of refining next-generation SME into commercializable products, as well as the revenues necessary for leading SME firms to invest in R&D. Investments in continued SME innovation help to ensure that American firms continue to reap the benefits that come with leadership in the SME industry, locking out Chinese SME firms from crucial feedback loops and revenue derived from leading global fabs. (The United States should avoid tariffs aimed at locking Chinese SME firms out from global markets—see Box 3.)

R&D funding. The U.S. government should fund pre-competitive R&D programs in partnership with U.S. SME firms, as well as allied

SME firms impacted by export controls on SME.¹²⁵ The IP generated by this funding could be licensed to all program participants. U.S. SME firms should also be given refundable tax credits for R&D and production.¹²⁶ In 2019, the U.S. semiconductor industry spent \$39.8 billion in R&D, while the U.S. government spent only \$1.7 billion on semiconductor-specific R&D and \$4.3 billion on semiconductor-related R&D. Public R&D has not much increased in decades, even while private R&D has grown considerably.¹²⁷ An increase in public R&D spending—including for SME—could help sustain U.S. and allied competitiveness. is overdue. The CHIPS for America Act, included in the NDAA for Fiscal Year 2021, authorizes a National Semiconductor Technology Center to conduct R&D into SME.¹²⁸ This Center should be sufficiently funded, and supplemented with additional R&D efforts.

Workforce development. The U.S. SME industry competes for and relies upon high-end talent¹²⁹—especially foreign-born. Promising options for strengthening the U.S. SME workforce include investing in research universities and STEM education, sustaining the Optional Practical Training program, avoiding country-based caps on green cards, and increasing the number of available employment-based visas.¹³⁰

Box 3: Impacts of tariffs on semiconductor manufacturing equipment

In 2018, the U.S. government announced tariffs on SME imports from China.¹³¹ Such tariffs could slow the growth of Chinese SME firms by depriving them of revenue and fabs’ product feedback to help SME firms go from a working prototype to a high-volume, high-yield, commercially-viable machine. Thus far, most Chinese SME firms have not managed to secure the cooperation of the world’s leading fabs, but this could change as Beijing focuses more resources on catching up in SME. For example, TSMC verified and began using AMEC’s etch equipment in 2018. Although TSMC does not use this equipment to etch the smallest features of these chips, access to the world’s leading contract chip manufacturer gives AMEC an advantage over its competitors, and demonstrates a high level of Chinese capability in etch relative to other SME sub-sectors.¹³²

However, such tariffs are risky and inadvisable for several reasons:

- Chinese SME firms currently gain little revenue from non-Chinese markets, making tariffs a solution in search of a problem.
- Tariffs shield top global SME firms from competition, relaxing pressure to innovate.
- Increased tariffs would escalate trade tensions, risking retaliatory Chinese tariffs.
- China's new strategy of fabs experimenting with indigenous SME serves as a next-best substitute for Chinese SME firms gaining the business of leading chipmakers.
- Tariffs could increase costs for non-Chinese SME firms with manufacturing operations in China.
- Under WTO rules, the United States must claim national security concerns for import restrictions. How far countries can go with such claims is unclear. Historically, the WTO has not questioned national security defenses raised against WTO challenges to trade restrictions, but has recently begun giving more guidance.¹³³ It is currently a grey area.

Conclusion

Japan in the early 1970s had virtually no presence in the SME industry. Within two decades, Japanese firms had joined U.S. firms at the leading edge across most SME sub-sectors, a position many of them still hold today.

Today, China hopes to replicate Japan's success. For now, the SME industry is the weakest part of China's semiconductor supply chain—but catching up to the leading edge is not impossible. Chinese SME firms currently have access to imports of some SME components and potentially billions of dollars in subsidies. They will also benefit to some degree from technology transfers from top global firms, including some degree of returnee talent. If Beijing is permitted to leverage these key inputs to SME progress, it may be sufficient to bring even China's weakest SME sub-sector, photolithography, to the leading edge.

Policymakers have a range of options to slow China's progress in SME. These options include export controls, investment controls, and promoting transparency on, and further studying, Chinese subsidies of SME firms. Findings also suggest the importance of strengthening the United States' infrastructure for S&T analysis—as well as the need to complement technology protection with investments in R&D and workforce development that actively promote continued U.S. SME innovation.

Appendix A: CSET Expert Survey Results

CSET sent a survey to 150 individuals identified as experts in the semiconductor industry over two waves in September and December 2019. Seven experts completed the survey: a fairly typical response rate for surveys requiring substantial time investment. This report draws on respondents' answers to four prompts; the sections below present the wording of each of four prompts, as well as respondents' answers, in full.

Question 1

Please rate the importance of the following resources for developing an internationally competitive SME industry in China. Rate by assigning a numerical value to the following resources indicating relative importance for a combined total of 100. You have the option to use "other" to enter a relevant resource that is not listed.

- More investment/funding: ____
- Access to blueprints and designs: ____
- Access to devices for reverse engineering: ____
- Talent with technical know-how (i.e. implicit knowledge, experience): ____

Table 8. Responses to Question 1

More investment/ funding	Access to blueprints and designs	Access to devices for reverse engineering	Talent with technical know- how
20	30	20	30
20	20	20	40
15	25	10	50
30	0	10	60
5	30	5	60
40	0	10	50
20	20	20	40

Question 2

Given current trends, how many years from now will China develop internationally competitive industries in the following areas? Please enter a numerical value or range.

- Etch equipment: ____
- Deposition equipment: ____

- Photolithography equipment: ____

Table 9. Responses to Question 2

Deposition equipment	Etch equipment	Photolithography equipment
5 to 10	5 to 10	10 to 15
15	15	25
5	5	10
20	20	20
5	5	5

Question 3

Would a change in China’s access to money and funding alter your estimated timelines?

- A. Definitely yes
- B. Probably yes
- C. Probably not
- D. Definitely not

Table 10. Talled responses to Question 3

A. Definitely yes	B. Probably yes	A. Probably not	A. Definitely not
1	1	5	0

Question 4

Would a change in China’s access to talent alter your estimated timelines?

- A. Definitely yes
- B. Probably yes
- C. Probably not
- D. Definitely not

Table 11. Talled responses to Question 4

A. Definitely yes	B. Probably yes	A. Probably not	A. Definitely not
3	4	5	0

Authors

Will Hunt and Dahlia Peterson, CSET Research Analysts, focused on research and writing for this report. Saif M. Khan, CSET Research Fellow, directed the project and contributed to research and writing. The authors contributed equally to this report and are therefore listed in alphabetical order.

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Endnotes

¹ Semiconductors include computer chips, which account for 81 percent of global semiconductor sales, as well as optoelectronics (10 percent), sensors (3 percent), and discretely (6 percent). “WSTS Semiconductor Market Forecast Fall 2020,” World Semiconductor Trade Statistics, December 1, 2020, https://www.wsts.org/esraCMS/extension/media/f/WST/4820/WSTS_nr-2020_11.pdf.

² Approximately one third of Japanese firms’ revenue growth may be attributable to the strengthening of the Japanese yen against the American dollar during the 1980s. *Global Competitiveness of U.S. Advanced-Technology Manufacturing Industries: Semiconductor Manufacturing Equipment and Testing Equipment* (Washington, DC: U.S. International Trade Commission, September 1991), <https://www.usitc.gov/publications/332/pub2434.pdf>.

³ Defense Science Board, *Report of the Defense Science Board Task Force on Defense Semiconductor Dependency* (Washington, DC: U.S. Department of Defense, February 1987), 8, 58, <https://apps.dtic.mil/dtic/tr/fulltext/u2/a178284.pdf>.

⁴ *Global Competitiveness*, U.S. International Trade Commission.

⁵ In December 2019, the Netherlands chose not to renew ASML’s license to sell EUV to Chinese firms, after negotiations with the United States. Alexandra Alper, Toby Sterling, and Stephen Nellis, “Trump Administration Pressed Dutch Hard to Cancel China Chip-Equipment Sale: Sources,” Reuters, January 6, 2020, <https://www.reuters.com/article/us-asmlholding-usa-china-insight-idUSKBN1Z50HN>. In December 2020, the U.S. Commerce Department added Chinese chipmaker SMIC to the entity list, requiring U.S. SME firms to obtain export licenses before shipping need an export license to sell to SMIC. “Commerce Adds China’s SMIC to the Entity List, Restricting Access to Key Enabling U.S. Technology,” U.S. Department of Commerce, December 18, 2020, <https://www.commerce.gov/news/press-releases/2020/12/commerce-adds-chinas-smic-entity-list-restricting-access-key-enabling>. And the U.S. House Foreign Affairs Committee recently proposed a bill to tighten multilateral export controls on shipments of SME to China and other arms-embargoed countries. *Revitalizing Multilateral Export Control Diplomacy for Critical Technologies Act*, H.R. 8329, 116th Cong. (2020).

⁶ “2020 SIA Factbook” (Semiconductor Industry Association, 2020), 5, https://www.semiconductors.org/wp-content/uploads/2020/04/2020-SIA-Factbook-FINAL_reduced-size.pdf.

⁷ However, as consolidation continues, governments may apply increasing antitrust scrutiny. Applied Materials' acquisition of Japanese SME firm Kokusai Electric Corporation is held up by approval from Chinese regulators. Ian King, "Applied Materials Lifts Bid for Kokusai to \$3.5 Billion," *Bloomberg*, January 4, 2021, <https://www.bloomberg.com/news/articles/2021-01-04/applied-materials-lifts-bid-for-kokusai-electric-to-3-5-billion>.

⁸ All five of these firms were among the top 250 U.S. patentees, with Applied Materials ranking 62nd. "2021 Patent 300 List," Harrity, accessed February 2, 2021, <https://harrityllp.com/patent300/>. By comparison, none of these companies were among the top 350 public companies by revenue. Andrea Murphy, Hank Tucker, Marley Coyne, and Halah Touryalai, "Global 2000," *Forbes*, May 13, 2020, <https://www.forbes.com/global2000/>.

⁹ The 35 percent value represents China's share of electronics equipment manufacturing. "2020 SIA Factbook," Semiconductor Industry Association, 12. However, China's share of semiconductor end-use is 20 percent. Dan Kim and John VerWey, "The Potential Impacts of the Made in China 2025 Roadmap on the Integrated Circuit Industries in the U.S., EU and Japan" (U.S. International Trade Commission, August 2019), 23, https://www.usitc.gov/publications/332/working_papers/id_19_061_china_integrated_circuits_technology_roadmap_final_080519_kim_verwey-508_compliant.pdf.

¹⁰ Brian Wang, "Future Tech Dominance – China Outnumber USA STEM Grads 8 to 1 and by 2030 15 to 1," *Next Big Future*, August 2, 2017, <https://www.nextbigfuture.com/2017/08/future-tech-dominance-china-outnumber-usa-stem-grads-8-to-1-and-by-2030-15-to-1.html>.

¹¹ In the semiconductor industry, new generations of chips are called nodes. According to Moore's Law, the industry typically introduces a new node every two years with double the transistor density as the previous node. In recent years, Moore's Law has begun to slow down. Prior to the 22 nm node, node names referred to the size of certain important features on a chip, such as the gate length of a transistor, and two chips at the same node typically had similar speed and power, even if they were made by different companies. After the 22 nm node, however, more exotic transistor shapes were introduced. Today, node names no longer refer to meaningful feature sizes. Thus, for example, Intel's "10 nm" node is more comparable in sophistication to TSMC's "7 nm" chip than to TSMC's "10 nm" chip.

¹² Unni Pillai, "The Emergence of Tools Suppliers in the Semiconductor Industry," SSRN, December 21, 2017, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3091894; Vu Luong, "EUV

Lithography Coming to Your Local IC Manufacturer! Soon,” Interuniversity Microelectronics Centre, May 16, 2018, 13, <https://eng.kuleuven.be/en/research/phd/arenberg-youngster-seminars/ays-pdf/20180516-luong-ays-final.pdf>; Chris Mack, “Milestones in Optical Lithography Tool Suppliers,” *Lithoguru* (blog), 2005, http://www.lithoguru.com/scientist/litho_history/milestones_tools.pdf.

¹³ For a more detailed account of China’s status across the entirety of the global semiconductor supply chain, including a more detailed breakdown of its leading SME firms, see Saif M. Khan, Alexander Mann, and Dahlia Peterson, “The Semiconductor Supply Chain: Assessing National Competitiveness” (Center for Security and Emerging Technology, January 2021), <https://cset.georgetown.edu/wp-content/uploads/The-Semiconductor-Supply-Chain-Issue-Brief.pdf>.

¹⁴ Khan et al., “The Semiconductor Supply Chain.”

¹⁵ Taipan Long, “China Micro Semiconductor: Daguo Heavy Equipment-7nm Chip Etching Machine Leader,” *eastmoney*, May 2, 2019, <http://finance.eastmoney.com/a/201905021112223192.html>.

¹⁶ Chinese SME firms gain revenue equal to 12 percent of the Chinese SME market. VLSI Research. Subtracting a limited set of known sales outside China by ASM Pacific and Hoson, we estimate the localization percentage is no greater than 8 percent, and likely lower.

¹⁷ For a basic description of these steps, see the series beginning with “Eight Major Steps to Semiconductor Fabrication, Part 1: Creating the Wafer,” Samsung Newsroom, April 22, 2015, <https://news.samsung.com/global/eight-major-steps-to-semiconductor-fabrication-part-1-creating-the-wafer>. For a full technical description on the order and interplay of these steps, see Robert J. Lopes, “Semiconductor Processing,” ECE 684: Advanced Microprocessor Systems, New Jersey Institute of Technology, Newark, NJ, <https://web.archive.org/web/20201004222514/https://web.njit.edu/~rlopes/Mod2.1.pdf>.

¹⁸ Mark LaPedus, “China’s Fab Tool Biz Heats Up,” *Semiconductor Engineering*, October 28, 2015, <https://semiengineering.com/chinas-fab-tool-biz-heats-up/>.

¹⁹ “Etching Equipment,” AMEC, accessed February 2, 2021, <https://www.amec-inc.com/products.html#Etch>.

²⁰ “China IC Ecosystem Report” (Milpitas, CA: SEMI, 2017 edition), 35.

²¹ These bottlenecks represent especially critical types of SME that Chinese firms cannot produce. Khan et al., “The Semiconductor Supply Chain.”

²² VLSI Research’s Chinese revenues and market shares for deposition, test, and assembly and packaging count data from ASM Pacific, which is headquartered in Singapore and listed on the Hong Kong stock exchange.

²³ “600 Series Scanner — IC Front-End Manufacturing,” SMEE, accessed February 2, 2021, http://www.smee.com.cn/eis.pub?service=homepageService&method=indexinfo&onclicknodeno=1_4_1_1.

²⁴ VLSI Research.

²⁵ “Yield” is the industry term for the percentage of chips produced in a wafer that are functional.

²⁶ ASML’s EUV technology became viable for mass chip production a decade after ASML sold its first EUV photolithography tool. SMEE has also stated that it plans to introduce a 28 nm ArF immersion photolithography tool by 2021 or 2022. “First China-Made 28nm Lithography Machine Expected to Be Delivered in 2021-2022,” *cnTechPost*, June 5, 2020, <https://cntechpost.com/2020/06/05/first-china-made-28nm-lithography-machine-expected-to-be-delivered-in-2021-2022/>; SMEE, “600 Series Scanner.”

²⁷ “First China-Made 28nm Lithography Machine,” *cnTechPost*, June 5, 2020, <https://cntechpost.com/2020/06/05/first-china-made-28nm-lithography-machine-expected-to-be-delivered-in-2021-2022/>.

²⁸ A stepper “steps” the silicon wafer between different locations while keeping the photomask in the same position, so that the photomask pattern can be transferred to different locations of the wafer to print more chips. Scanners can move not only the wafer, but also the photomask. This has a number of advantages, including allowing the use of smaller and thus less expensive lenses.

²⁹ Zhang Yangfei and Zhang Zhihao, “New Machine Raises Country's Image in Photolithography,” *China Daily*, November 30, 2018, <https://web.archive.org/web/20201029214848/https://www.chinadaily.com.cn/a/201811/30/WS5c006df2a310eff30328be90.html>.

³⁰ Guan Li, “How Many Generations of Technology is the Difference Between Chinese Lithography and Foreign Top Companies?,” *EET*, June 14, 2019, <https://www.eet-china.com/news/201906140941.html>.

³¹ The tool uses an i-line light source, typically suitable for only the 600 nm and earlier nodes. Zhang Yangfei and Zhang Zhihao, “New Machine Raises Country's Image,” *China Daily*, November 30, 2018, <https://web.archive.org/web/20201029214848/https://www.chinadaily.com.cn/a/201811/30/WS5c006df2a310eff30328be90.html>.

³² “Current Status of the Integrated Circuit Industry in China — IC Special Equipment Industry,” *Journal of Microelectronic Manufacturing* 2, no. 1 (March 29, 2019): 6, <http://www.jommpublish.org/p/26/>.

³³ VLSI Research.

³⁴ VLSI Research; Pillai, “The Emergence of Tools Suppliers.”

³⁵ “The Development History of Domestic Lithography Machine,” *Oriental Fortune Network*, June 8, 2019, <https://baijiahao.baidu.com/s?id=1635770743568025033&wfr=spider&for=pc>; “International Roadmap for Devices and Systems,” *IEEE*, 2020, https://irds.ieee.org/images/files/pdf/2020/2020IRDS_MM.pdf; “Technology Node,” WikiChip, accessed February 2021, https://en.wikichip.org/wiki/technology_node; “IC Area,” SMEE, accessed February 2021, <http://www.smee.com.cn/>.

³⁶ Experts were only asked about only three SME sub-sectors. The survey did not ask about the process control sub-sector, though this is another area of weakness for China.

³⁷ Consider a highly optimistic scenario for China’s photolithography sub-sector, in which SMEE grows at a rate of 60 percent per year over the next decade, perhaps with the help of government subsidies. Even at this rate of growth, which has only been sustained twice in the history of the sub-sector (first by Nikon and then by ASML), SMEE’s revenues would amount to just half the size of China’s domestic market for photolithography equipment. China is projected to have 24 percent of the world’s semiconductor manufacturing capacity by 2030, which suggests it should have a comparable share of the photolithography market at that time. Antonio Varas, Raj Varadarajan, Jimmy Goodrich, and Falan Yinug, “Government Incentives and US Competitiveness in Semiconductor Manufacturing” (Boston Consulting Group and Semiconductor Industry Association, September 2020), 7, <https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in->

[Semiconductor-Manufacturing-Sep-2020.pdf](#). Because Chinese chipmakers lag behind the leading edge, much of this demand will likely be for pre-EUV photolithography tools. Simply meeting this domestic demand, then, would be a significant feat, and would allow Chinese SME firms to grow considerably—even if they continue to fall short of the goals outlined in the Made In China 2025 Technical Roadmap.

³⁸ William Hannas and Huey-Meei Chang, “China’s Access to Foreign AI Technology” (Center for Security and Emerging Technology, September 2019), https://cset.georgetown.edu/wp-content/uploads/CSET_China_Access_To_Foreign_AI_Technology-1.pdf.

³⁹ Tax subsidies are another important source of financial support from the Chinese government. In July 2020, China’s State Council issued “Policies for Promoting the High-Quality Development of the Integrated Circuit Industry and Software Industry in the New Era,” which exempts Chinese SME firms—as well as semiconductor design, material, packaging, and testing companies—from corporate income taxes for two years, and from 75% of corporate income taxes for the following three years. The policy also halves the statutory tax rate for these firms. “The State Council’s Issues Concerning the Promotion of Integrated Circuit Industry and Notice of Several Policies for the High-Quality Development of the Software Industry,” *The State Council: People’s Republic of China*, August 4, 2020, http://www.gov.cn/zhengce/content/2020-08/04/content_5532370.htm.

⁴⁰ Li Tao, “How China’s ‘Big Fund’ is Helping the Country Catch Up in the Global Semiconductor Race,” *South China Morning Post*, May 10, 2018, <https://www.scmp.com/tech/enterprises/article/2145422/how-chinas-big-fund-helping-country-catch-global-semiconductor-race>. The Peterson Institute of International Economics (PIIE) pointed out this 138.7 billion yuan was far greater than its announced 120 billion yuan target. Tianlei Huang, “Government-Guided Funds in China: Financing Vehicles for State Industrial Policy,” June 17, 2019, *Peterson Institute for International Economics*, <https://www.piie.com/blogs/china-economic-watch/government-guided-funds-china-financing-vehicles-state-industrial-policy>.

⁴¹ “The Big Fund Will Invest Another 2.1 Billion Yuan! Invest in These Three Semiconductor Companies One After Another,” *eeworld*, June 5, 2018, http://www.eeworld.com.cn/manufacture/article_2018060526153.html; Hu Wei, “Inventory of the Development Status of Domestic Semiconductor Equipment Companies,” *ElecFans*, August 18, 2018, <http://www.elecfans.com/d/731554.html>.

⁴² Huang, “Government-Guided Funds in China.”

⁴³ *Measuring Distortions in International Markets: The Semiconductor Value Chain* (Paris: Organisation for Economic Cooperation and Development, December 12, 2019), <https://doi.org/10.1787/8fe4491d-en>.

⁴⁴ “Big Funds Trigger a “Chain Reaction” of China’s Integrated Circuits,” Xinhua, May 2, 2018, http://www.xinhuanet.com/tech/2018-05/02/c_1122768897.htm.

⁴⁵ Liu Qianqian and Ma Haoran, “National Defense Informatization In-Depth Report Series—The Time to Replace Imports with Independently Controllable Domestically Produced Versions is Now [国防信息化深度系列报告——自主可控国产化替代时不我待]” (Pacific Securities (太平洋证券), April 2018), 16, http://pdf.dfcfw.com/pdf/H3_AP201804271132194582_1.pdf.

⁴⁶ Calculated by combining the second round of 200 billion yuan, the first round’s 138.7 billion yuan, and the sub-funds at the local level, which Chinese industry sources estimate are at least 514.5 billion yuan. *Measuring Distortions*, OECD; “The Second Phase of the Big Fund is About to Emerge the Integrated Circuit Industry is Expected to Break Through,” *China Securities Journal*, March 2, 2018, http://www.cs.com.cn/ssqs/gsxw/201803/t20180302_5727479.html.

⁴⁷ Historically, Chinese state-owned enterprises in the semiconductor industry performed poorly. Douglas B. Fuller, *Paper Tigers, Hidden Dragons: Firms and the Political Economy of China’s Technological Development* (Oxford: Oxford University Press, 2016), 118, 156.

⁴⁸ “The Semiconductor Sector Has Once Again Risen Strongly, and the National Big Fund is Making a Move to Buy Shares in IoT Chip Companies,” *Financial*, April 1, 2020, <https://baijiahao.baidu.com/s?id=1662750252454874392>. As mentioned earlier, a localization rate refers to the percentage (by revenue) of SME bought by Chinese customers from Chinese SME firms.

⁴⁹ Ngor Luong and Zachary Arnold, “Understanding Chinese Government Guidance Funds” (Center for Security and Emerging Technology, March 2021), <https://cset.georgetown.edu/wp-content/uploads/CSET-Understanding-Chinese-Government-Guidance-Funds.pdf>.

⁵⁰ SEMI, “China IC Ecosystem Report”; “The Chinese Government Promotes the Semiconductor Industry,” *ElecFans*, December 5, 2017, <http://www.elecfans.com/d/594786.html>; Wei, “Inventory of the Development Status”; “The Second Phase,” *China Securities Journal*.

⁵¹ “Big Funds,” Xinhua.

⁵² For firms throughout the global semiconductor supply chain, state subsidies amount to less than fifty percent of revenues. *Measuring Distortions*, OECD. Thus, in the short term SMEE likely will not receive more than 20 million dollars in subsidies per year.

⁵³ Li Keqiang, “Full Text: Report on the Work of the Government,” <http://en.people.cn/n3/2018/0403/c90000-9445262.htm>.

⁵⁴ “Big Funds,” Xinhua.

⁵⁵ Josh Horwitz, “China Semiconductor Fab SMIC Gets \$2.2 Bln Investment from Gov't Funds Amid Global Chip Spat,” Reuters, May 18, 2020, <https://www.reuters.com/article/china-semiconductor-smic/china-semiconductor-fab-smic-gets-22-bln-investment-from-govt-funds-amid-global-chip-spat-idUSL4N2D019Y>.

⁵⁶ Xie Yu, “China is Powering Ahead with Its Tech Development Blueprint, It’s Just Not Talking About It,” *South China Morning Post*, July 15, 2019, <https://www.scmp.com/business/banking-finance/article/3018689/china-powering-ahead-its-tech-development-blueprint-its>; “Don’t Do Something Wrong,” *Xueqiu*, December 25, 2019, <https://xueqiu.com/8186228019/137965308>.

⁵⁷ The remaining two respondents said “Probably yes” and “Definitely yes.”

⁵⁸ “A Backgrounder on Extreme Ultraviolet (EUV) Lithography,” ASML, January 18, 2017, <https://medium.com/@ASMLcompany/a-backgrounder-on-extreme-ultraviolet-euvlithography-a5fccb8e99f4>; Andreas Thoss, “EUV Lithography Revisited,” *Laser Focus World*, August 29, 2019, <https://www.laserfocusworld.com/blogs/article/14039015/how-does-the-laser-technology-in-euv-lithography-work>. ASML itself also produces, in its Wilton, Connecticut factory, EUV components that handle and align reticles and wafers. Michael J. Miller, “ASML: Making EUV Components in Connecticut,” *PC Magazine*, December 13, 2017, <https://www.pcmag.com/news/asml-making-euv-components-in-connecticut>.

⁵⁹ For example, Japan-based Gigaphoton is the most likely alternative supplier to Cymer.

⁶⁰ In 2019 ASML categorized 221 of its 5003 suppliers as “critical.” “Integrated Report 2019,” ASML, 2019, 197, <https://www.asml.com/>

</media/asml/files/investors/financial-results/a-results/2019/2019-integrated-report-based-on-us-gaap.pdf>.

⁶¹ The U.S. Commerce Control List and the Wassenaar Arrangement list “specially designed components” of EUV tools under ECCN 3B001 and Section 3.B.1, respectively.

⁶² For example, ASML may have set up exclusive agreements with many of its most specialized suppliers, such that ASML’s competitors (including those in China) cannot purchase these components even in the absence of export controls.

⁶³ “Asimer: Exporting DUV Lithography Machines to China Does Not Require a License/Why Hasn't China Produced Extreme Ultraviolet EUV Lithography Machines,” *Euchina*, October 16, 2020, <http://webcache.googleusercontent.com/search?q=cache:fJE4gHfVa0IJ:www.euchina.org.cn/portal/article/index/id/1401.html>.

⁶⁴ Andrea Gilli and Mauro Gilli, “Why China Has Not Caught Up Yet: Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage,” *International Security* 43, no. 3 (February 15, 2019): 141-189, https://www.mitpressjournals.org/doi/pdf/10.1162/isec_a_00337.

⁶⁵ *Global Competitiveness*, U.S. International Trade Commission.

⁶⁶ Jay Stowsky, “The Weakest Link: Semiconductor Production Equipment, Linkages, and the Limits to International Trade,” BRIE Working Paper #27, September 1987, <https://econpapers.repec.org/paper/cdlucbrie/qt9dr7q4pr.htm>.

⁶⁷ Peter Wood, Alden Wahlstrom, and Roger Cliff, “China’s Aeroengine Industry” (China Aerospace Studies Institute, March 2020), https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/Infrastructure/CASI_Aeroengines%20041520.pdf?ver=2020-04-22-133912-480.

⁶⁸ “Chinese Spies Conspired to Steal Jet-Engine Technology, U.S. Alleges,” *The Los Angeles Times*, October 31, 2018, <https://www.latimes.com/business/la-fi-china-jet-engine-20181031-story.html>.

⁶⁹ “US Court Issues Final Judgment in Favor of ASML against XTAL,” ASML, May 4, 2019, [https://www.asml.com/en/news/press-releases/us-court-issues-final-judgment-in-favor-of-asml-against-xtal-\(58788\)](https://www.asml.com/en/news/press-releases/us-court-issues-final-judgment-in-favor-of-asml-against-xtal-(58788)).

⁷⁰ For example, a major hacking campaign targeting a wide range of intellectual property from seven Taiwanese chip firms has been linked to mainland China,

and more loosely to the state-sponsored Chinese hacking group Winnti. Andy Greenberg, “Chinese Hackers Have Pillaged Taiwan's Semiconductor Industry,” WIRED, August 6, 2020, <https://www.wired.com/story/chinese-hackers-taiwan-semiconductor-industry-skeleton-key/>.

⁷¹ Six out of seven surveyed semiconductor industry experts indicated that each of these methods are typically used by semiconductor companies to prevent know-how transfers; one expert said cybersecurity measures are not frequently used. One expert additionally noted that semiconductor companies employ red-teaming to identify information security risks.

⁷² James A. Lewis, “Learning the Superior Techniques of the Barbarians: China's Pursuit of Semiconductor Independence” (Center for Strategic and International Studies, January 2019), 8, https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/190115_Lewis_Semiconductor_v6.pdf.

⁷³ Alex Webb, “Why Might China Want to Steal These Silicon Secrets?,” Bloomberg, April 11, 2019, <https://www.bloombergquint.com/opinion/why-might-china-want-to-steal-these-silicon-secrets-from-asml>.

⁷⁴ Global Competitiveness, U.S. International Trade Commission.

⁷⁵ Gilli, “Why China Has Not Caught Up Yet.”

⁷⁶ Michael Kremer, “The O-Ring Theory of Economic Development,” *The Quarterly Journal of Economics* 108, no. 3 (August 1993), <https://www.jstor.org/stable/2118400>.

⁷⁷ James Bessen, *Learning by Doing: The Real Connection Between Innovation, Wages, and Wealth* (New Haven, CT: Yale University Press, April 28, 2015), 33, 186.

⁷⁸ Marco Iansiti and Jonathan West, “From Physics to Function: An Empirical Study of Research and Development Performance in the Semiconductor Industry,” *The Journal of Product Innovation Management* 16, no. 4 (July 1999), <https://www.sciencedirect.com/science/article/abs/pii/S073767829800068X>.

⁷⁹ China's broader semiconductor industry is also most bottlenecked by lack of tacit know-how. “McKinsey on Semiconductors” (McKinsey & Company, 2011), 27, https://www.mckinsey.com/~media/mckinsey/dotcom/client_service/semiconductors/pdfs/mosc_1_revised.ashx.

⁸⁰ In another notable case, the National Nuclear Security Administration took ten years and millions of dollars to re-engineer a classified material called FOGBANK—required for manufacturing nuclear weapons—that their staff in the 1980s knew how to make. *Nuclear Weapons Journal* 2 (2009): 20–21, https://www.lanl.gov/orgs/padwp/pdfs/nwj2_09.pdf.

⁸¹ Gilli, “Why China Has Not Caught Up Yet.”

⁸² Complexity is difficult to define, let alone measure, but cost per unit is one crude metric. EUV photolithography tools cost more than \$120 million per unit, while F-22 jets cost more than \$300 million per unit. Because most SME equipment costs less than an EUV scanner, this suggests that most SME equipment is less complex than an F-22, though some may be within the same order of magnitude of complexity. Cost per unit correlates with the speed of diffusion of the technology. C. Wilson, A. Grubler, N. Bento, S. Healey, S. De Stercke, and C. Zimm, “Granular Technologies to Accelerate Decarbonization,” *Science* 368, no. 6486 (April 2020): <https://science.sciencemag.org/content/sci/368/6486/36.full.pdf>.

⁸³ “China's Semiconductor Dilemma! This is All!,” Sohu, November 23, 2018, https://www.sohu.com/a/277476577_202311.

⁸⁴ Andrew Leonard, “Betrayal: A Silicon Valley Way of Life,” Salon, January 4, 2008, https://www.salon.com/2008/01/03/chips_and_treachery/.

⁸⁵ There is some chance that Chinese nationals working abroad use LinkedIn less frequently than those from other countries, as LinkedIn is not as widely used in China as it is in the United States and the Netherlands. This would lead to an underestimate of the proportion of Chinese workers at top SME firms. Our analysis is based on publicly accessible versions of LinkedIn.

⁸⁶ This analysis excludes data from Tokyo Electron, a Japanese firm, because Japanese workers rarely use LinkedIn.

⁸⁷ The top 5 SME firms by revenue—Applied Materials, ASML, Tokyo Electron, Lam Research, and KLA—capture 66.3 percent of the market. These 5 companies employ approximately 57,000 workers, implying a total SME employee headcount of about 84,000, not including Chinese SME firms, which capture 2 percent of the market.

⁸⁸ To estimate the number of Chinese workers at these firms, this analysis assumes that those who attend Chinese universities are Chinese nationals: this biases our results upward slightly, though the effect is likely negligible. More

significantly, some workers at the four firms listed will not have LinkedIn accounts: this likely biases the results downward. Our analysis is based on publicly accessible versions of LinkedIn.

⁸⁹ Will Hunt and Remco Zwetsloot, “The Chipmakers: U.S. Strengths and Priorities for the High-End Semiconductor Workforce” (Center for Security and Emerging Technology, September 2020), <https://cset.georgetown.edu/wp-content/uploads/CSETThe-Chipmakers.pdf>.

⁹⁰ Based on publicly accessible analysis of LinkedIn.

⁹¹ Clair Brown and Greg Linden, *Chips and Change: How Crisis Reshapes the Semiconductor Industry* (Cambridge, MA: MIT Press, August 19, 2011), 167–168.

⁹² Brown and Linden, *Chips and Change*, 167–168.

⁹³ However, at least one Chinese SME firm has succeeded in contracting with TSMC. AMEC’s plasma etching tools are currently in use by TSMC at the 5 nm node. Lena Li and Jessie Shen, “AMEC 5nm Plasma Etching Tools Verified by TSMC,” *DigiTimes*, December 21, 2018, <https://www.digitimes.com/news/a20181221PD207.html>. While this is a significant accomplishment, AMEC’s tool likely is not useful for creating the finest features on 5 nm chips, such as FinFETs.

⁹⁴ Chad P. Bown, “How the United States Marched the Semiconductor Industry into Its Trade War with China” (Peterson Institute for International Economics, December 2020), 2, <https://www.piie.com/sites/default/files/documents/wp20-16.pdf>.

⁹⁵ “CST, a Subsidiary of Wanye Enterprise, etc. Take a Stake in the Core Chain and Lead the Investment in the Northern Innovation Center to Help the Industrial Ecology,” *Sina*, October 27, 2020, <https://finance.sina.com.cn/stock/relnews/cn/2020-10-27/doc-iiznctkc7939111.shtml>.

⁹⁶ Ji Liu, “Recent Development of patent litigation in China,” *Lexology*, July 23, 2020, <https://www.lexology.com/library/detail.aspx?g=a04229d2-df2a-47f3-9e33-fe9e4adbeb19>; Renjun Bian, “Many Things You Know About Patent Infringement in China Are Wrong,” *SSRN*, October 1, 2017, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3063566.

⁹⁷ Jonathan Masters and James McBride, “Foreign Investment and U.S. National Security,” Council on Foreign Relations, August 28, 2018, <https://www.cfr.org/background/foreign-investment-and-us-national-security>.

⁹⁸ Chinese investment fund Hubei Xinyan was blocked from acquiring U.S.-based SME firm Xcerra. Greg Roumeliotis, “U.S. Blocks Chip Equipment Maker Xcerra's Sale to Chinese State Fund,” Reuters, February 22, 2018, <https://www.reuters.com/article/us-xcerra-m-a-hubeixinyan/u-s-blocks-chip-equipment-maker-xcerras-sale-to-chinese-state-fund-idUSKCN1G703H>. China’s Fujian Grand Chip Investment Fund was blocked from acquiring Germany-based SME firm Aixtron. Nigel Cory and Robert D. Atkinson, “Why and How to Mount a Strong, Trilateral Response to China’s Innovation Mercantilism” (Information Technology & Innovation Foundation, January 13, 2020), <https://itif.org/publications/2020/01/13/why-and-how-mount-strong-trilateral-response-chinas-innovation-mercantilism>.

⁹⁹ The Exon-Florio Amendment, passed in 1987, changed the powers and importance of CFIUS, which existed previously but had been a relatively obscure entity.

¹⁰⁰ For more detailed versions of these recommendations, see *Second Quarter Recommendations* (Washington, DC: National Security Commission on Artificial Intelligence, 2020), https://www.nscai.gov/wp-content/uploads/2021/01/NSCAI-Q2-Memo_20200722.pdf.

¹⁰¹ For example, 16 EU member states currently have investment screening policies and several others have plans to adopt such policies. European Commission, “List of Screening Mechanisms Notified by Member States,” last updated January 14, 2021, https://trade.ec.europa.eu/doclib/docs/2019/june/tradoc_157946.pdf.

¹⁰² Renato Antonini et al., “Dutch Government Plans Retroactive Foreign Investment Screening in View of COVID-19 Crisis,” *Jones Day*, June 2020, <https://www.jonesday.com/en/insights/2020/06/dutch-government-plans-retroactive-foreign-investment-screening-in-view-of-covid19-crisis>; “Amendment Bill of the Foreign Exchange and Foreign Trade Act,” Ministry of Finance, Japan, October 21, 2019, https://www.mof.go.jp/english/international_policy/fdi/20191021.html; Matthew P. Goodman, “With or Without Them,” *Center for Strategic and International Studies*, December 18, 2018, <https://www.csis.org/analysis/or-without-them>.

¹⁰³ William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Pub.L. 116–283, 116th Cong. (2020).

¹⁰⁴ “BRIEF-Suzhou Secote Precision Electronic To Invest 236.8 Mln Yuan For Stake In Japan's Optima,” *Yahoo Finance*, May 10, 2019, <https://finance.yahoo.com/news/brief-suzhou-secote-precision-electronic-103738482.html>; Zhang Yushuo, “China's Jingce Electronic to Spend USD23.8

Million for 61% of Japan's Wintest," Yicai Global, August 1, 2019, <https://www.yicai.com/news/china-jingce-electronic-to-spend-usd238-million-for-61-of-japan-wintest>; "Intang Intelligent Control: Acquired Pioneer Microtechnology and Obtained Approval from Japan, and Its Own Equipment Includes Nissan Lithography Machine," Sohu, August 24, 2020, https://www.sohu.com/a/414601444_260616; "Notice of the Transfer of Subsidiary (stock transfer)," Nihon Dempa Kogyo Co., Ltd., June 3, 2020, https://www.ndk.com/en/news/2020/1191103_e.pdf; "Resurgence of Mergers and Acquisitions? It is Reported That the Shanghai Semiconductor Equipment Materials Fund Intends to Acquire a Japanese Optical Inspection Equipment Manufacturer," EDA365, February 17, 2020, <https://www.eda365.com/article-94719-1.html>.

¹⁰⁵ Second Quarter Recommendations, National Security Commission on Artificial Intelligence.

¹⁰⁶ For a recent example where an individual transferred controlled technical data to China, see "Former Raytheon Engineer Sentenced for Exporting Sensitive Military Related Technology to China," U.S. Department of Justice, November 18, 2020, <https://www.justice.gov/opa/pr/former-raytheon-engineer-sentenced-exporting-sensitive-military-related-technology-china>.

¹⁰⁷ Key SME chokepoints include tools for EUV photolithography, argon fluoride immersion photolithography, imprint lithography, e-beam lithography, laser lithography, resist processing, metrology, inspection, advanced ion implantation, advanced etching, advanced deposition, wafer and mask handling, and testing for advanced logic chips. Khan et al., "The Semiconductor Supply Chain."

¹⁰⁸ Unite! Chinese companies or cooperate with Japan's Nikon and Canon to develop lithography machines?," NetEase, October 13, 2020, <https://www.163.com/dy/article/FOR4N3KU05119JRD.html>.

¹⁰⁹ Hunt and Zwetsloot, "The Chipmakers."

¹¹⁰ Deemed export controls may be useful for EUV tools even though they are made only in the Netherlands, because they are sold to chipmakers such as Intel, an American firm. However, in cases where China already has access to a given tool, such as ArF immersion photolithography equipment, deemed export controls may offer less value.

¹¹¹ Saif M. Khan, "U.S. Semiconductor Exports to China: Current Policies and Trends" (Center for Security and Emerging Technology, October 2020), 19,

<https://cset.georgetown.edu/research/u-s-semiconductor-exports-to-china-currentpolicies-and-trends/>.

¹¹² Khan, “U.S. Semiconductor Exports to China.”

¹¹³ See ECCN 3B001 of the U.S. Commerce Control List and Section 3.B.1. of the Wassenaar Arrangement.

¹¹⁴ In January 2021, the Department of Defense designated AMEC a “Communist Chinese military company,” which could trigger application of military end-user export controls. “DOD Releases List of Additional Companies, In Accordance with Section 1237 of FY99 NDAA,” U.S. Department of Defense, January 14, 2021, <https://www.defense.gov/Newsroom/Releases/Release/Article/2472464/dod-releases-list-of-additional-companies-in-accordance-with-section-1237-of-fy/>. Chinese military end-users export controls are subject to more stringent controls than other entities in China. For details, see Khan, “U.S. Semiconductor Exports to China.”

¹¹⁵ For example, the United States should use the de minimis and/or foreign-produced rule to ensure U.S. controls cover U.S. firms’ SME produced abroad, such as in Singapore, which is now a significant exporter of SME. Bown, “How the United States Marched the Semiconductor Industry,” 27.

¹¹⁶ Bureau of Industry and Security, *U.S. Space Industry “Deep Dive” Assessment: Impact of U.S. Export Controls on the Space Industrial Base* (Washington, DC: Department of Commerce, February 2014), 30, <https://www.bis.doc.gov/index.php/documents/technology-evaluation/898-spaceexport-control-report/file>.

¹¹⁷ Gilli, “Why China Has Not Caught Up Yet”; David Eimer, “China’s Stealth Fighter ‘Based on U.S. Technology,’” *The Telegraph*, January 23, 2011, <https://www.telegraph.co.uk/news/worldnews/asia/china/8277090/Chinas-stealth-fighter-based-on-US-technology.html>.

¹¹⁸ Stowsky, “The Weakest Link.”

¹¹⁹ Saif M. Khan, “Securing Semiconductor Supply Chains” (Center for Security and Emerging Technology, January 2021), <https://cset.georgetown.edu/wp-content/uploads/Securing-Semiconductor-Supply-Chains-Policy-Brief.pdf>; Saif M. Khan and Carrick Flynn, “Maintaining China’s Dependence on Democracies for Advanced Computer Chips” (Brookings Institution and Center for Security and Emerging Technology, April 2020), <https://cset.georgetown.edu/wp->

[content/uploads/Khan-Flynn%E2%80%94Maintaining-Chinas-Dependence-on-Democracies.pdf](#).

¹²⁰ For example, the previous section identified EUV light sources supplied by the American firm Cymer as a potential chokepoint: losing access to this component would increase China's struggles in developing a working EUV photolithography tool. But unilateral export controls on exports of Cymer's light source to China could be counterproductive: unless Japan coordinates on export controls with the United States, the Japanese firm Gigaphoton might step in to fill the gap left by Cymer.

¹²¹ Tarun Chhabra, William Hannas, Dewey Murdick, and Anna Puglisi, "Open-Source Intelligence for S&T Analysis" (Center for Security and Emerging Technology, September 2020), <https://cset.georgetown.edu/wp-content/uploads/CSET-Policy-Recommendation-OSINT-One-Pagers.pdf>.

¹²² William Hannas and Huey-Meei Chang, "China's STI Operations" (Center for Security and Emerging Technology, January 2021), <https://cset.georgetown.edu/wp-content/uploads/CSET-Chinas-STI-Operations.pdf>.

¹²³ Relevant agencies responsible for export controls covering semiconductor technologies include the Bureau of Industry and Security at the Department of Commerce, the Defense Technology Security Administration at the Department of Defense, and the Directorate of Defense Trade Controls and the Office of Export Control Cooperation at the Department of State.

¹²⁴ By comparison, non-Chinese chipmakers receive subsidies equal to less than five percent of their revenue. *Measuring Distortions*, OECD, 84.

¹²⁵ Funding should focus on pre-competitive R&D, which produces large social returns but avoids market distortions. *International Technology Transfer Policies* (Paris: Organisation for Economic Cooperation and Development, January 24, 2019), 31, <https://doi.org/10.1787/7103eabf-en>. *Measuring Distortions*, OECD, 39.

¹²⁶ Currently, the United States provides smaller R&D tax incentives than most other OECD countries. John Lester and Jacek Warda, "Enhanced Tax Incentives for R&D Would Make Americans Richer" (Information Technology & Innovation Foundation, September 2020), <http://www2.itif.org/2020-enhanced-tax-incentives-rd.pdf>.

¹²⁷ "2020 SIA Factbook," Semiconductor Industry Association, 17; "Sparking Innovation: How Federal Investment in Semiconductor R&D Spurs U.S. Economic

Growth and Job Creation” (Semiconductor Industry Association, June 2020), 5, https://www.semiconductors.org/wp-content/uploads/2020/06/SIA_Sparking-Innovation2020.pdf.

¹²⁸ William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Pub.L. 116–283, 116th Cong. (2020).

¹²⁹ “SIA Workforce Roundtable” (Semiconductor Industry Association, March 26, 2018), https://www.semiconductors.org/wp-content/uploads/2018/06/Roundtable_Summary_Report_-_FINAL.pdf.

¹³⁰ Hunt and Zwetsloot, “The Chipmakers.”

¹³¹ Semiconductor Industry Association, “Proposed Modification of Action Pursuant to Section 301: China’s Acts, Policies, and Practices Related to Technology Transfer, Intellectual Property, and Innovation,” USTR-2018-0026, September 6, 2018, 1, <https://www.semiconductors.org/wp-content/uploads/2019/03/SIA-Submission-on-301-Tariffs-September-6-Final.pdf>.

¹³² Taiwanese chipmakers do purchase a few other Chinese SME tools; for example, NAURA’s deposition and etch tools and Hoson’s assembly and test tools. VLSI Research.

¹³³ In one recent exception, the WTO adjudicated a national security defense raised by Russia to a challenge filed by Ukraine. In that case, the WTO found Russia’s national security defense to be sufficient to allow Russia’s restrictions on Ukrainian traffic in transit through Russia to Mongolia. “Russia — Measures Concerning Traffic in Transit,” World Trade Organization, DS512, https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds512_e.htm.