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Semiconductor Manufacturing Equipment

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Introduction

With geopolitical competition intensifying, U.S. economic security policy has undergone significant changes. Primarily, the United States has expanded economic security measures to take new defensive actions around critical and emerging technologies (CETs). Such efforts center on denying China access to key foundational technologies—particularly advanced semiconductors that support dual-use applications such as artificial intelligence (AI).

The administrations of Presidents Donald Trump and Joe Biden have expanded economic security measures regarding China's access to CETs. Export controls are an increasingly common tool in U.S. economic security efforts, and National Security Advisor Jake Sullivan has called them a "new strategic asset in the U.S. and allied toolkit."[1] Under the Biden administration, the federal government has implemented two major rounds of semiconductor export controls, one in October 2022 and a second in October 2023. Additional controls may be forthcoming as the United States aims to use trade restrictions to deny China access to leading-edge semiconductors, thus limiting China's ability to develop military and dual-use technologies such as advanced AI systems.[2]

The potential benefits of such a strategy to economic and national security are obvious. They include maintaining technological superiority for modern military capabilities and intelligence gathering. Washington sees clear, legitimate risks associated with the proliferation of highly advanced semiconductors among its adversaries. A sensible U.S. export control policy focused on preserving technological superiority is a measured response.

Export controls, however, are a double-edged sword.[3] When a nation decides to implement controls, it effectively restricts its companies' market share. If controls negatively affect a nation's technological champions, policymakers may inadvertently compromise their country's status as a long-term technology leader. The loss in sales decreases these tech champions' revenue and, in some cases, redirects it to foreign competitors, potentially reducing future investments in innovation for key U.S. firms.[4]

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If the relative costs imposed on China's technological progression and the corresponding benefits to U.S. national security outweigh the costs to U.S. industry and innovation, then Washington may well view these impacts as a necessary price. However, China's semiconductor ecosystem—through its own strategies and through government support—has managed to undermine the effectiveness of many of the controls meant to keep Chinese firms behind their Western counterparts.[5] For one, Chinese companies have found ways to access U.S. technology by circumventing controls. These efforts have been widely written about and include using overseas shell companies to purchase controlled products, as well as leveraging domestic technology trading networks to redirect technology via firms that are exempt from controls.[6]

Beyond circumvention efforts, U.S. export controls have helped facilitate a farther-reaching unintended consequence: China has set its domestic semiconductor ecosystem on a path *toward removing U.S. technology altogether*. Chinese government and commercial actors have deployed two key long-term strategies to create ex-U.S. supply chains for semiconductor technologies across the value chain. These strategies, which represent the focus of this series of papers by the CSIS Economics Program and Scholl Chair in International Business, include the following:

1. **Design-out:** supplanting existing U.S. and allied semiconductor technologies with *comparable* technologies, from either
   a. Chinese firms; or
   b. third-country (non-U.S. and non-Chinese) firms
2. **Design-around:** developing *new* technologies that do away with an entire category of controlled technology in the semiconductor supply chain

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Design-Out and Design-Around

As discussed in the Economics Program and Scholl Chair in International Business's introductory report in this series, which covers advanced packaging, China is rapidly accelerating the design-out of U.S. technologies from semiconductor supply chains in response to existing–and in anticipation of future–U.S. export controls.[7] It has pursued this goal, in part, by increasingly adopting domestic firms' technologies.[8] China's semiconductor industry has rapidly pivoted toward made-in-China technology over the last few years, facilitated by expanded government investment and other incentives, as well as preferential procurement practices by Chinese semiconductor companies.[9]

There is also evidence of increased Chinese adoption of third-country suppliers within semiconductor supply chains. For instance, competitors from Japan, the Netherlands, Taiwan, Israel, and South Korea have increasingly leveraged China's chip market as a growth engine, winning new Chinese customers and increasing existing customers' wallet share as the impacts of U.S. export controls constrain the competitiveness of U.S. companies.[10] This third-country design-out threat potentially shifts semiconductor industry leadership toward foreign competitors, some of whom offer China the very technologies U.S. companies are barred from selling.

In addition, China is looking to design around U.S. export controls–in other words, innovate to achieve advanced semiconductor capabilities using approaches not modeled on U.S. technologies. Importantly, this trend means China is beginning to innovate rather than copy foreign technology in the chip industry. As discussed in the packaging report, a shift away from a "fast-follower" approach toward a more innovative approach would represent a key change in U.S.-China technological competition—one that potentially threatens long-term U.S. innovation leadership.

It would be one thing if China's design-out and design-around strategies affected only leading-edge semiconductor technologies, which are the primary targets of U.S. export controls. However, China's pivot away from U.S. technology has affected not only the leading edge but also foundational, or "trailing-edge," semiconductor technologies.[11] Chinese and third-country firms want to avoid dealing with the high regulatory and financial burdens of U.S. export controls, which are complex, stricter than other nations' in coverage and enforcement, and fast evolving. As a result, Chinese and foreign companies selling to the Chinese market are newly incentivized to avoid using U.S. technology where possible. Additionally, the ambiguity of the controls means that firms may opt to overcomply with export regulations and avoid selling or purchasing U.S. technologies—even if the products technically fall outside of the controls—for fear of dealing with costly litigation.[12]

The United States, for its part, looks to press forward with stricter controls.[13] This threat of stricter controls, in turn, encourages China to design out and design around other U.S. technologies to hedge against future regulations. In this way, tightening unilateral U.S. export controls is having a ripple effect across the Chinese—and global—semiconductor ecosystem, threatening to undermine U.S. leadership and leverage in the sector.

3

Overview

Semiconductor Manufacturing Equipment

This paper focuses on China's design-out and design-around strategies related to semiconductor manufacturing equipment (SME)—the machines critical to making chips. China's access to such equipment has become increasingly important to its national semiconductor ambitions as expanding U.S. and allied export controls limit Chinese access to leading global chip manufacturers such as Taiwan Semiconductor Manufacturing Company (TSMC), Samsung, and Intel.

SME is a strong example of the design-out issue. Chinese companies are increasingly replacing U.S. producers one-to-one in Chinese semiconductor manufacturing facilities, or fabs.[14] As procurement practices in Chinese fabs shift toward an anywhere-but-the-United-States approach, SME sales are also shifting toward third-country toolmakers.[15]

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The United States would benefit economically and strategically from continuing to sell some SME technology to China. These benefits do not apply to technologies that are highly specific to advanced dual-use technology and cannot be acquired elsewhere or rapidly developed domestically. For example, ASML's sales of extreme ultraviolet (EUV) lithography provide a choke point for Chinese technological advancement into fabrication processes like 3 nanometers (nm) and is a prime example of the power of export controls.[16] But for less niche and non-sole-sourced tools, unilateral and broad export controls risk U.S. technology champions losing out on revenue while China maintains its access to the same technology, either via industry indigenization efforts or shifting purchases to third countries.

This paper explores why SME is important to semiconductor technological innovation, what types of U.S. SME are facing design-out and design-around risks, and what implications those risks carry for U.S. economic and national security.

Why Is Semiconductor Manufacturing Equipment Important?

Making semiconductors is impossible without a wide array of specialized, highly advanced machinery. Each manufacturing plant, or fab, contains an average of 1,200 multi-million-dollar tools—all of which are critical to chip production.[17] This group of tools transforms a thin piece of crystalline silicon or other semiconducting material into a fabricated wafer containing billions—if not trillions—of nanometric transistors precisely etched onto a tiny surface area (often just 300 millimeters).[18] Capital expenditures (CapEx) on SME constitute an estimated 75 percent of total CapEx on fab construction, and some tools reach the size of a double-decker bus, costing upward of $150 million.[19]

Semiconductor fabrication, both for leading-edge process nodes and mature chip technologies, is one of the most complex manufacturing processes on the planet—in large part due to the machinery required. For instance, ASML's EUV lithography devices have been called "the most complicated machine humans have built."[20] As a result, advancements in SME technology have historically represented a key driver of semiconductor industry innovation. High-quality SME is also critical to the economics of scaled production, as any imprecision in a finished chip's structure or composition can affect performance and reduce a fab's production yield. All this means that a fab's access to tools is a leading determinant of how competitive its technology is on a global scale.

SME is often divided into front-end equipment used in wafer fabrication and processing, such as lithography, etch, deposition, and cleaning, and back-end equipment used for assembly, packaging, dicing, bonding, and testing. Because the advanced packaging brief covers assembly and packaging equipment, this brief focuses on fabrication and test equipment in evaluating design-out and design-around risks.

Four types of SME across front-end and back-end equipment are under significant threat of design-out: (1) deposition, (2) etching, (3) process control, and (4) testing. While discussions of the semiconductor supply chain often group testing with assembly and packaging, the authors include testing within SME here for two reasons: First, testing plays a key role in front-end wafer fabrication (as well as in back-end processes like assembly and packaging), as it takes place continually throughout the production life cycle. Second, the design-out and design-around dynamics of testing equipment are more like those of chipmaking tools rather than those of assembly or packaging technologies. As in the areas of etching, deposition, and process control, the United States is home to leading competitors in testing equipment, which are facing design-out risks from foreign manufacturers. For these reasons, testing is included as part of SME in this report.

The following section introduces each category of SME as well as the key U.S. and global players associated with it. The primary takeaway is that U.S. manufacturers, alongside competitors primarily from U.S.-allied countries such as Japan and the Netherlands, have historically held leading shares of global equipment markets—particularly for chipmaking technologies at the leading edge.[21] This leadership underscores the high stakes of any shift in global market share because of U.S. export controls. U.S. companies have much revenue and technological leadership to lose to new Chinese companies—as well as Dutch, Japanese, Israeli, German, and other foreign firms, many of which are well positioned in equipment markets to grab a share of the U.S. market.

Deposition

The deposition process involves specialized tools depositing thin films of conducting, isolating, or semiconducting materials on the wafer.[22] Deposition takes place throughout the fabrication stage and often occurs in multiple sequential iterations along with processes such as photolithography and etching.[23] It plays a key role in enabling miniaturization in semiconductors, as it can create protective barriers to prevent atomic-level interference. Deposition can also help strengthen or weaken an electric field and connect transistors with other devices and power sources.

There are various types of deposition used in wafer fabrication. U.S. companies such as Lam, Applied Materials, Plasma-Therm, and Veeco are key players across most types of deposition tools.[24] The two areas discussed in depth here are epitaxy and atomic layer deposition, given their potential for design-out by Chinese supply chains.

Epitaxy—also known as "epi"—involves depositing a near-perfect crystalline layer directly on top of the wafer substrate.[25] Epitaxy growth typically occurs during the beginning of the wafer fabrication process, following wafer polishing and preceding the sequences of lithography, etching, and other deposition processes.[26] Adding an epitaxial layer helps fabs better control doping wafers with impurities and can introduce a different material than that used in wafer "bulk" materials. As a result, epitaxy facilitates more effective electron transmission, a key goal in advanced chipmaking.[27]

Epitaxy innovation plays an important role in the ongoing evolution of both chip fabrication and advanced packaging.[28] Epitaxy is important to nonclassical wafer substrates (i.e., nonsilicon) such as gallium arsenide (GaAs), gallium nitride (GaN), and silicon carbide (SiC), which play a key role in critical technologies such as aerospace and defense applications and electric vehicles.[29] An emerging technology within the field of epitaxy is remote epitaxy.[30] Remote epitaxy is the growth of a thin epitaxial layer that is aligned—but not in contact—with the substrate.[31] This technique has a plethora of applications in advanced packaging, particularly three-dimensional (3D) packaging designs, in which multiple chips are stacked to enhance bandwidth while reducing power consumption and footprint.[32]

The epitaxy equipment market includes tools used for metal-organic chemical vapor deposition, high-temperature chemical vapor deposition, and molecular beam epitaxy. Leading suppliers are based in Germany, the United States, and Japan—as well as China. Key companies in terms of 2020 market share include Germany's Aixtron, the United States' Veeco, China's Advanced Micro-Fabrication Equipment Inc., China (AMEC), and Japan's Tokyo Electron (TEL).[33]

Atomic layer deposition (ALD) is an advanced type of chemical vapor deposition (CVD) that adds layers consisting of a single atom of thickness onto a wafer.[34] It is key to leading-edge chip designs due to the importance of controlling layer thickness and composition in fabricating advanced chips, whose features are small enough that the industry is running up against the physical limits of miniaturization.[35] There are two key types of ALD: thermal ALD and plasma-enhanced ALD (PEALD).[36] Whereas the former relies solely on chemical precursors to deposit the atomic layer, PEALD uses plasma to provide reaction energy for the process, enabling greater control over film characteristics.[37]

Netherlands-based ASM is the leader in ALD, particularly PEALD, holding above 50 percent of the market, according to investor materials.[38] Additional key suppliers include Japan's Kokusai, TEL, and Optorun, as well as the United States' Lam Research. As of 2020, China's Naura had a "negligible" share.[39]

Etching

The etching process involves carving a precise pattern onto the wafer by selectively removing layers of material using either liquid or gas chemicals.[40] Etching takes the pattern created during photolithography—during which a light selectively removes parts of a photoresist coating based on a photomask design—and applies this pattern permanently to the material layer below. Etching occurs multiple times in fabrication and creates a complex pattern of cavities where the thin film layer has been removed.

There are two main types of etching tools: dry and wet.[41] Dry etching tools use gases to engrave the wafer and are necessary to create the circuitry on leading-edge chips. Atomic layer etching tools are particularly important for advanced process node production due to their greater control and precision.[42] Wet etching, which uses liquid chemicals to engrave the wafer, is less common than dry etching for advanced process nodes due to the challenges of creating complex structures. However, it is cheaper and less risky, making it commonly used to clean wafers. Because etching also plays a key role in mature chip technologies, both dry and wet etching tools are critical to semiconductor manufacturing.

The United States and Japan are the world's leading suppliers of etching equipment, followed by China and South Korea.[43] Lam Research, Applied Materials, and KLA all have strong shares in global dry and wet etching markets. Japan's TEL, Hitachi, and Screen are other notable players. South Korea-based SEMES represents a growing wet etching player. Finally, in China, AMEC, Naura, and Kingsemi are notable small providers of etching tools.

Process Control

Process control refers to using monitoring tools in semiconductor manufacturing to ensure quality control. It takes place concurrently with other stages of fabrication and involves metrics like the purity of wafer materials, transistor dimensions, and chip conductivity. As chip dimensions get smaller, variations at the molecular level represent a larger share of an integrated circuit's dimensions, making process control increasingly important in fabrication.[44] Ongoing industry shifts, like the switch from single patterning to multiple patterning and from planar to 3D transistors, mean that variations increasingly come from the material quality or the deposition process, calling for more advanced control tools.[45]

Process control is important to both advanced and mature node production, as it has a key impact on yield. Wafer production yield, or the percentage of individual chips (dies) per wafer that make it through the final probe testing stage, is a critical metric for fabs due to their high per-unit operating costs.[46] Process control technology helps enable a higher yield, thus improving profitability by minimizing wasted output.[47]

Key types of semiconductor process control technologies include photomask inspection and repair tools, process monitoring equipment, wafer inspection equipment, and wafer-level inspection packaging tools. U.S. companies hold strong market share across all key types of tools. Notable U.S. players include Applied Materials, KLA, Keithley Instruments, Keysight Technologies, Onto Innovation, Nanotronics, and Thermo Fisher. Japan and Germany are home to most leading competitors, such as Lasertec, Rigaku, and Screen in Japan and Zeiss and Bruker in Germany. Chinese players are smaller and include Shanghai Micro Electronics Equipment (SMEE), Jingce, and Raintree.[48]

While various players compete across the entire process control ecosystem, individual markets are often highly concentrated among a few players. For instance, the market for wafer-level packaging inspection tools is dominated by one U.S. and one Israeli firm.[49] As a result, the impact of export controls on a single company's positioning can have a significant effect on global market shares.

Testing

Semiconductor testing occurs at multiple stages during fabrication and packaging, helping ensure defective chips do not make it into final packages. Chips go through up to six stages of testing: (1) wafer acceptance, (2) wafer sort, (3) wafer-level burn-in, (4) package test, (5) burn-in test, and (6) testing at the system level.[50] Testing equipment has taken on increased importance and industry value as the cost of testing devices and the potential losses associated with manufacturing defective dice have risen in response to advances in chip design and applications such as advanced graphics processing units, which are commonly used to train AI models.

Key types of semiconductor testing tools include burn-in test equipment, handlers and probes, linear and discrete testing tools, and system-on-a-chip testing equipment. Japanese and U.S. firms hold leading market shares in different parts of the industry.[51] Notable Japanese companies include Advantest, Tesec, and Accretech. U.S. players include Teradyne, National Instruments, and Cohu. South Korean firms such as UniTest and DI Corporation are also key participants. Chinese capabilities have historically been more limited.

4

How the EAR Impacts U.S. and Foreign Toolmakers

The Commerce Department's October 7, 2022, rules, implemented under the Export Administration Regulations (EAR), require licensing of U.S. equipment and persons involved in certain types of chip manufacturing.[52] Affected technologies include equipment used in the production of "logic chips with non-planar transistor architectures . . . of 16nm or 14nm, or below; DRAM memory chips of 18nm half-pitch or less; [and] NAND flash memory chips with 128 layers or more." The regulation's October 2023 updates tighten controls to include some older technologies, such as immersion deep ultraviolet (DUV) lithography.[53]

Products newly subject to the EAR include both items in the United States and "all U.S. origin items wherever located."[54] This inclusion means that U.S.-based multinational companies producing SME (not to mention other semiconductor technologies) cannot avoid the controls when selling to China, even when relying on factories abroad.

For companies based outside the United States, determining whether the EAR applies is more complex. Foreign-made items may be subject to the EAR in two ways: (1) falling under a U.S. foreign direct product rule (FDPR) or (2) exceeding the de minimis threshold of "controlled" U.S.-origin content.[55] Ostensibly, both rules apply the U.S. controls extraterritorially, leveraging the frequent presence of U.S. technology in third-country products.

Foreign Direct Product Rules

FDPRs apply the EAR to foreign-made items if they are the "direct product" of certain types of U.S.-origin equipment, software, or other technology, and are destined for designated countries. Specifically, FDPRs empower the Bureau of Industry and Security (BIS) to require licenses for exports of certain foreign-made products if listed U.S. technology was directly used to produce them or produce key parts of the plants that were used to manufacture the products, such as a tool or a piece of software—even if a controlled U.S. component or system does not appear in the product.[56]

Three FDPRs limit Chinese access to semiconductor technologies: the Entity List (EL), Advanced Computing, and Supercomputer FDPRs.[57] These FDPRs differ in terms of the products, companies, and countries that they cover. The EL FDPR, introduced in May 2020 by the Trump administration, applies U.S. export controls to products destined for hundreds of Chinese (and other foreign) companies and their subsidiaries.[58] These restrictions vary based on the products involved as well as the type of EL classification applicable to the purchaser company. Their reach has continued to grow as the U.S. Department of Commerce has added Chinese firms to the EL.[59] The Advanced Computing FDPR applies the EAR to a narrower range of products meeting certain performance parameters and based on the destination country rather than the destination company. Originally aimed at China, the Advanced Computing FDPR has expanded the list of destination countries to include the countries China likely uses to avoid controls, such as Kazakhstan and Mongolia.[60] Finally, the Supercomputer FDPR applies a country and end-use scope to encompass any items subject to the EAR that are used to produce supercomputers, which are defined based on compute capacity and system dimensions.[61]

The FDPRs and de minimis rules aim to limit the ability of third-country suppliers (who face less strict export controls from their governments) to replace U.S. suppliers in Chinese markets. However, their current efficacy in this regard is questionable. Multiple U.S. SME companies told CSIS that these restrictions are not stopping foreign toolmakers from replacing them in Chinese fabs, a complaint that has also been raised to U.S. officials.[62] While public evidence supporting this trend remains limited, a New York Federal Reserve study from April 2024 on the impacts of U.S. semiconductor export controls showed that non-U.S. firms that sell to Chinese semiconductor companies experienced "higher revenues and profitability . . . following the inclusion of the Chinese targets in the U.S. export control lists."[63]

De Minimis Rules

De minimis rules apply the EAR based on the inclusion of U.S.-origin controlled inputs in foreign-exported goods destined for specific countries. Notably, unlike the FDPRs, use of de minimis rules requires that the exported goods directly contain products produced in the United States that fall under the EAR.[64] This differs from the FDPR's broader threshold of goods being the "direct product" of certain U.S.-origin technologies or inputs (that do not need to be included in the actual goods being shipped). In cases where the shipment of the U.S. inputs to the final country destination by themselves (i.e., when not incorporated into a final product) would require a license, a de minimis calculation is necessary for the foreign export of the product that contains the inputs. Depending on the type of product and country destination, different de minimis thresholds—or the minimum percentage of U.S.-origin controlled items as a share of "fair market value" at which the EAR applies (typically 10 or 25 percent)—are relevant to the specific good.[65] If the good exceeds the relevant de minimis threshold, an export waiver is required, pursuant to the EAR. For some products (e.g., certain lithography tools), a zero percent de minimis threshold applies, meaning that inclusion of any U.S.-origin controlled input automatically applies the EAR.[66]

Notably, the United States has been relatively hesitant to apply the FDPR to foreign exports of semiconductor technology due to the rule's negative perception among U.S. allies. Allied governments and companies have sharply criticized the FDPR as an overreach of U.S. export control authority. During recent discussions in which the United States threatened to expand application of the FDPR, foreign governments reportedly said they would not cooperate with enforcement of this application, potentially threatening FDPR expansion.[67] Although the U.S. government is reportedly preparing an expansion to the FDPR and EL that would increase restrictions on foreign exports, a Reuters report indicated that category A:5 countries—which include Japan, the Netherlands, and South Korea—would be exempt from the expanded FDPR.[68] The exclusion of countries home to leading toolmakers like ASML and Tokyo Electron belies the U.S. government's continued hesitation to use the FDPR on key allies in the semiconductor supply chain.

Enforcement of extraterritorial applications of the EAR is also a challenge. For semiconductor controls, enforcement challenges are exacerbated by needing to know the node process for which the technology is used, in order to determine whether the extraterritorial rules apply. As an example, SME used in the production of "advanced-node integrated circuits" does not have a de minimis level in terms of U.S. content, whereas SME for less mature chipmaking does.[69] For shipments of finished chips, the node process is self-evident, based on the exported product itself. However, for SME and other inputs, the type of process node manufactured using the product may be less transparent to suppliers. For instance, the same types of etch equipment may be used in a wide range of process nodes, a practice known in the industry as "CapEx recycling." Therefore, suppliers could unintentionally sell some tools used for advanced nodes to Chinese customers, as these customers can lie about the process node they are using the tools for. Additionally, the burden falls on the company to determine whether the foreign-made item is subject to the EAR, further challenging enforcement.[70]

Interestingly, the New York Federal Reserve study described an increase in revenues for third-country firms despite including firms ostensibly subject to the extraterritorial restrictions (via FDPR or de minimis) in its data set. The authors admitted that this had the potential to bias "estimates towards finding a decline in revenues by non-U.S. firms that sell to Chinese targets."[71]

These findings suggest that the United States is applying the EAR less restrictively to third-country firms than U.S. firms, even where the FDPR or de minimis restrictions are meant to apply—another indication of potential challenges facing enforcement.

Even when fully enforced, FDPR and de minimis requirements are potentially avoidable by removing U.S. technologies from supply chains. Industry participants reported to CSIS that the EAR is incentivizing foreign toolmakers to minimize the use of U.S. technologies, services, and personnel in supply chains to avoid restricted trade with China. For example, one individual noted that a Japanese toolmaker was removing U.S. components from its supply chains and publicizing its products as outside U.S. EAR authority—a practice the individual suggested was widespread across SME markets globally.[72] Reports of these supply chain shifts suggest that, at least for some third-country toolmakers, reliance on U.S. technology is low enough to make avoiding the existing FDPR and de minimis thresholds possible.

In 2023, the Netherlands and Japan adopted their own export controls following U.S. diplomatic efforts.[73] However, these restrictions remain less stringent than U.S. controls in terms of end use and servicing personnel, giving Japanese and Dutch companies greater ability to sell to Chinese customers and provide on-the-ground support.[74] Additionally, other key supplier countries such as South Korea, Israel, and Germany have not adopted similar export controls.[75] Under the existing set of international export controls, foreign toolmakers continue to face significantly weaker restrictions on access to the Chinese market than U.S. companies.

A final risk of the current EAR in terms of creating unequal market access for U.S. and foreign companies is overcompliance. As one public commentator argued to BIS,

The October 7 IFR is so complex that only a small group of people with significant experience in the EAR and semiconductors can fully understand the rulemaking . . . Many small and medium enterprises, or even large foreign multinationals, not highly versed in these details will either not know if they are following the rule, or out of an abundance of caution, "over-comply" by restricting legitimate exports and trade not otherwise subject to these rules.[76]

While the October 2023 update simplifies calculations and identifies flags to help companies determine compliance, challenges remain in terms of understanding the breadth of the restrictions, which are highly technical and continually evolving.[77]

In other words, the EAR's complexity and ambiguity risk encouraging U.S. toolmakers to pull back from Chinese markets—even in places where they are not legally required to do so. For instance, the previously mentioned New York Federal Reserve study also showed that U.S. firms were more likely to terminate relations with Chinese customers following the export controls, even with those not directly targeted by the controls, and less likely to form new Chinese customer relationships—potentially due to concerns about unintentionally violating restrictions.[78] This risk of overcompliance also makes it more likely that third-country companies will design out U.S. companies, facilities, and personnel, even in areas not covered by export controls, to ensure they avoid the regulations.

5

Chinese Firms Designing Out U.S. Firms in SME

As U.S. economic and national security policy has become more stringent, Chinese businesses and policymakers have accelerated the semiconductor industry's shift away from U.S. inputs.[79] China's SME industry historically has failed to achieve technological parity with foreign toolmakers due to factors such as the smaller size of its companies and, as a result, its reduced capacity to invest in research and development (R&D).[80] Instead of buying domestic, leading Chinese chipmakers such as Semiconductor Manufacturing International Corporation (SMIC), Hua Hong Semiconductor, and Yangtze Memory Technologies (YMTC) have sought out the most advanced chipmaking technology available—which is often of U.S. origin. For instance, Applied Materials, KLA, and Lam Research all held large market shares in Chinese chip markets as of 2022. That same year, China's SME localization rate (the share of tools produced domestically) was 21 percent.[81] A 2021 report by Georgetown's Center for Security and Emerging Technology estimated a localization rate of just 8 percent.[82]

However, strong evidence suggests that China's procurement approach has shifted since late 2022, with the removal of U.S. technology emerging as a primary industry objective. In 2023, China's SME localization rate nearly *doubled* year over year to reach 40 percent.[83] A *South China Morning Post* article recently reported that the "unwritten rule" for Chinese fabs was 70 percent self-sufficiency (made in China) in SME and that firms were achieving "significant progress" for key types of chipmaking equipment, with the exceptions of lithography, ion implantation, and inspection and metrology (parts of process control).[84]

This design-out trend results from increasing top-down pressure from government officials and growing bottom-up commercial incentives for Chinese companies to minimize exposure to present—and future—U.S. regulatory actions. In the SME space, China's semiconductor industry is pursuing design-out through two main approaches: (1) increased procurement from and investment in Chinese toolmakers and (2) replacement of U.S. SME technology with products from third-country firms.

An April 2024 quote in the *Financial Times* by a YMTC investor neatly summarizes China's general design-out strategy for SME:

> If Chinese companies have equipment that can be used, [YMTC] will use it. If not, it will see if countries other than the US can sell to it. . . . If that doesn't work, YMTC will develop it together with the supplier.[85]

Design-Out via Chinese Toolmakers

In China, the export controls from October 7, 2022, accelerated a joint government-industry effort to build a domestic semiconductor supply chain for chipmaking equipment.[86] De-Americanizing Chinese semiconductor supply chains has been a Chinese objective for decades.[87] However, Chinese firms frequently ignored this top-down policy goal and sourced large shares of chipmaking equipment from abroad, including from U.S.-based companies.[88]

The Trump administration's April 2018 imposition of sanctions and export controls on ZTE represented a major turning point in pushing China to take steps toward reducing U.S. reliance, particularly for semiconductors.[89] These efforts went into overdrive following the October 7 export controls, which created immediate existential challenges for the Chinese semiconductor industry's access to key technologies. As a result, the controls catalyzed a coordinated response by both government and private sector entities. Central, provincial, and local government entities—as well as chipmaking firms such as Huawei, SMIC, YMTC, Hua Hong, and others—have rapidly expanded efforts to replace U.S. chipmaking technology with technology from Chinese suppliers. Nowhere in the industry has this shift been clearer than in SME.

Top-down government efforts focus on putting pressure on domestic chipmakers to procure Chinese SME. For instance, some companies told CSIS that Chinese customers are facing mandates from government officials to buy most chipmaking equipment from an approved "white list" of domestic companies. These sourcing goals can overrule traditional business performance metrics such as yield, benefitting Chinese toolmakers even in cases where quality is lower relative to U.S. firms. China is also investing heavily in SME production and innovation, including via the $47.5 billion third phase of its so-called Big Fund and by increasing industry involvement in state-backed research.[90]

At a bottom-up commercial level, Chinese fabs increasingly see advantages to using Chinese chipmaking tools wherever possible. Chinese firms have diversified supply chains away from U.S. and other foreign suppliers to mitigate risks associated with current export controls—as well as the threat of future controls. For instance, leading foundries such as YMTC are increasingly collaborating with leading Chinese toolmakers to access replacement parts and help Chinese companies quickly develop SME technology.[91] Chinese private investors are also increasingly investing in semiconductor companies, including toolmakers, attracted by public investment and the growing preference for Chinese suppliers.[92]

Based on publicly available data and interviews with industry participants, the CSIS Economics Program and Scholl Chair in International Business identified evidence of the design-out phenomenon taking place in at least four types of SME: (1) deposition, (2) etching, (3) process control, and (4) testing. These areas receive less attention than EUV lithography but nonetheless represent key technologies in the semiconductor manufacturing process. Notably, it is tougher to establish "choke points" using U.S. export controls for these areas than, for example, lithography tools and advanced metrology tools, meaning there are fewer obstacles to Chinese and third-country companies replacing U.S. technologies in Chinese fabs.

Two chipmaking equipment companies in particular—Naura Technology Group and AMEC—have been the largest beneficiaries of increased investment and innovation in Chinese SME supply chains. These companies represent the best evidence of the design-out of U.S. companies via Chinese suppliers.[93] Other key players include lithography developer SMEE, etching and glue developer Kingsemi, and test equipment provider Jingce. Chinese SME firms increasingly include smaller start-ups taking advantage of new openings in the domestic market, such as Shanghai-based Crystal Growth and Energy Equipment, which went public in early 2023.[94]

Table 1 summarizes key players in the Chinese SME space, their product focus areas, and historical global leaders based in the United States and its allies.

The growing revenues of Chinese toolmakers offer key evidence of the design-out phenomenon.[95] The Chinese consultancy CINNO Research released a 2023 analysis showing that the revenues of China's 10 largest SME companies increased by 39 percent in the first half of the year compared to the previous period in 2022.[96] AMEC, for its part, saw a 32 percent rise in sales in 2023.[97] Company executives identified strong demand from domestic firms as a key driver of growth. In August 2023, AMEC's chairman and CEO announced his firm had developed a road map to replace foreign-produced tools with domestic alternatives.[98] Naura saw its 2023 revenues increase by around 50 percent year over year.[99] As with AMEC, reports attribute Naura's rapid growth to China's desire to remove U.S. inputs from the domestic semiconductor fabrication market. AMEC and Naura are no exception—a wide variety of Chinese toolmakers have seen explosive domestic sales growth in the two years since the U.S. export controls.

There is also evidence of Chinese toolmakers winning market share away from U.S. companies, indicating that growing Chinese revenues are not just the result of top-line Chinese market growth. Historically, Chinese toolmakers could secure only a small share of key equipment markets, even within China.[100] From January to August 2023, however, local manufacturers won 47 percent of all machinery equipment tenders from Chinese foundries, according to an analysis by Huatai Securities.[101] An August 2023 article by the *South China Morning Post* reported that AMEC's share of one type of etching equipment is expected to hit 60 percent "in the near future," increasing from

Table 1: Product Portfolio of Chinese Original Equipment Manufacturer

Company	Litho	Etching	Resist	CVD	PVD	Ion Implant	CMP	Cleaning	Metrology
Global Leader	**ASML**	**LAM**	**TEL**	**AMAT**	**AMAT**	**AMAT**	**AMAT**	**SCREEN**	**KLA**
NAURA 002371.SZ		✓		✓	✓			✓	
AMEC 688012.SS		✓							
ACMR ACMR.US								✓	
SMEE Private	✓								
PNO 603690.SS								✓	
Kingsemi 688037.SS			✓						
Jingce 300567.SZ									✓
Wanye 600641.SS									✓
Raintree Private									
Mattson Private		✓	✓						
Hwatsing Private							✓		
Plotec Private				✓					

Source: Kyriakos Petrakakos, "U.S. Semiconductor Export Controls Might Actually Give China the Edge," The China Project, June 15, 2023, https://thechinaproject.com/2023/06/15/semiconductor-export-controls-a-catalyst-for-chinese-development/.

24 percent in October 2022—attributed to the fact that "once-dominant US chip equipment maker Lam Research saw its mainland sales drop sharply."[102] Notably, many U.S. toolmakers are still seeing increasing sales to China due to surging industry growth.[103] However, companies told CSIS that this growth is significantly below what it would otherwise be in the absence of design-out practices.[104]

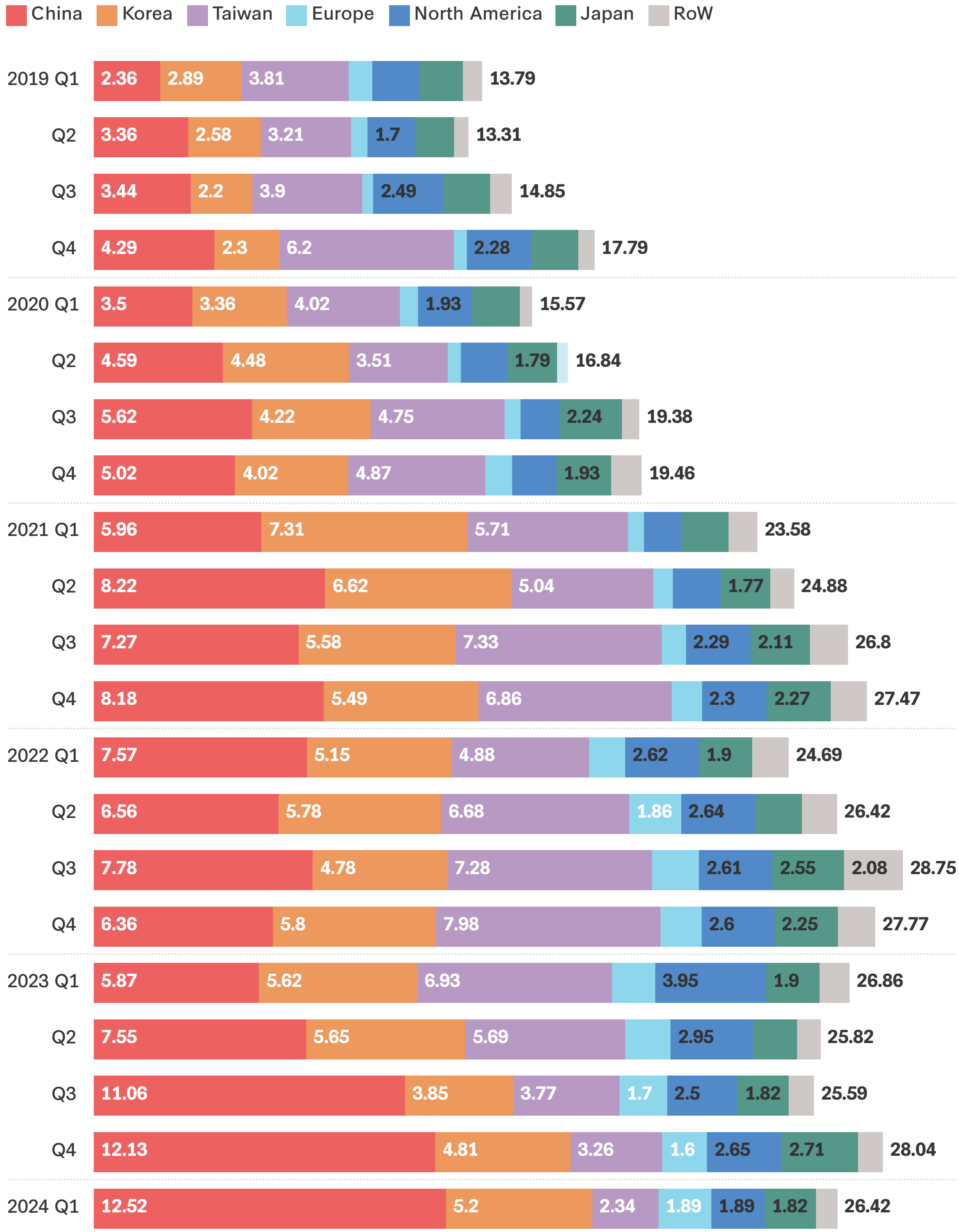
Beyond the observable increases in revenue and market share, reporting suggests that the Chinese semiconductor industry is publicly showing great enthusiasm for locally produced semiconductor tools and components. In March 2024, SEMICON China, a major semiconductor industry conference held in Shanghai, saw increased participation of domestic tool manufacturers and the notable absence of rival U.S. firms.[105] Reuters also reported that several domestic Chinese semiconductor equipment companies leaned into marketing strategies encouraging Chinese fabs to buy local at SEMICON: "More [Chinese] manufacturing facilities are willing to use materials prescribed by Chinese firms, a trend that has certainly been accelerated by U.S. sanctions."[106] The report mentions that while Chinese domestic firms may produce semiconductor manufacturing tools and components of slightly lesser quality, China is quickly catching up to its foreign counterparts. Furthermore, Chinese semiconductor products are sold at significantly cheaper prices than those of rival firms in other countries.

Design-Out via Third-Country Toolmakers

There has been significant reporting on Chinese tools replacing U.S. tools in the Chinese market.[107] However, less attention has been paid thus far to the other strategy enabling China's design-out: the increased substitution of tools from third countries—or countries other than the United States and China—in place of U.S. technology.

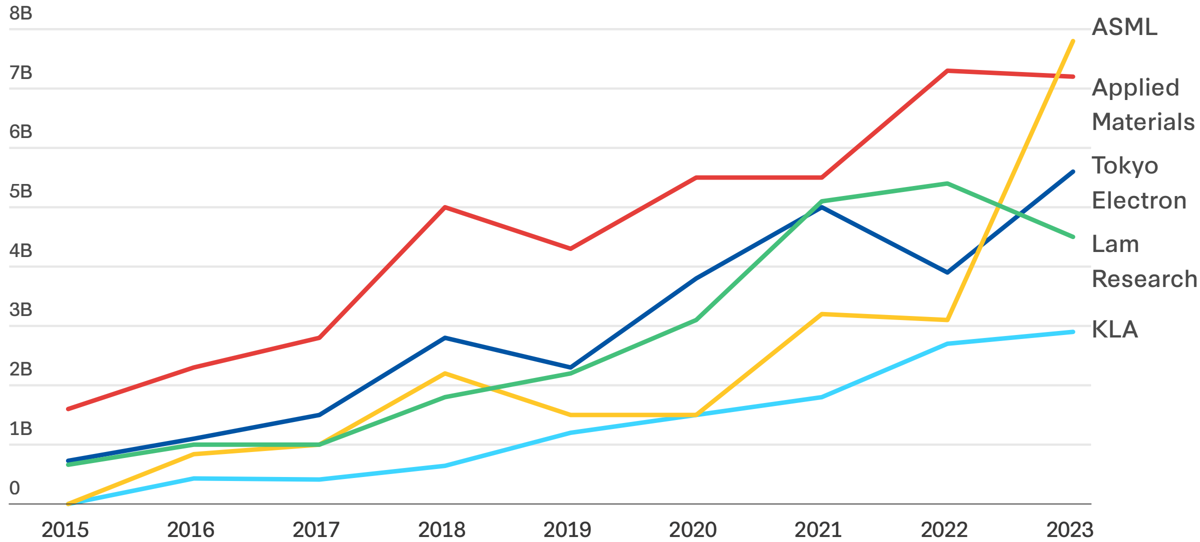
While Chinese buyers are increasingly apt to buy from domestic toolmakers, China is still a large buyer of foreign-made tools. Foreign SME helps fulfill technological capabilities not yet developed in China's market and provides a helpful blueprint for Chinese firms developing new tools. Since early 2023, Chinese fabs have gone on a shopping spree, amassing tools from both domestic and foreign suppliers. The most recent data, as of the first quarter of 2024, suggest that Chinese buying represents an unprecedented 45 percent of revenue for major Western toolmakers, nearly double the share of revenue recorded a year prior (see Figures 1 and 2).[108] Some of this revenue is going to U.S. toolmakers. According to fiscal year 2023 financials, China still represents the largest geographic share of sales for Applied Materials, KLA, and Lam Research. In fact, the dramatic investment boom in China's semiconductor industry and practices like equipment stocking in case of future restrictions have helped some U.S. toolmakers grow in the near term.[109]

Figure 1: Global Semiconductor Equipment Market Revenues by Region, 2019–Present



Source: SEMI, "Semiconductor Manufacturing Monitor," October 11, 2024, https://www.semi.org/en/products-services/market-data/manufacturing-monitor.

Figure 2: Sales to China for Select U.S. and Foreign Toolmakers, 2015–23



Source: Mackenzie Hawkins, Ian King, and Takashi Mochikuzi, "US Floats Tougher Trade Rules to Rein in China Chip Industry," Bloomberg.com, July 17, 2024, https://www.bloomberg.com/news/articles/2024-07-17/us-considers-tougher-trade-rules-against-companies-in-chip-crackdown-on-china.

However, there is evidence that China is increasingly redirecting business away from U.S. firms to non-U.S. foreign companies as part of its design-out strategy. CSIS Scholl Chair conversations with SME industry participants revealed reports that Chinese customers are increasingly selecting third-country toolmakers—such as firms based in Japan, Israel, South Korea, Germany, the Netherlands, and Taiwan—over U.S. companies in procurement decisions.[110] Specifically, several U.S. toolmakers told CSIS they rapidly lost share to third-country suppliers in Chinese foundries subsequent to the export regulations,[111] which is unsurprising in the context of explicit rhetoric by Chinese companies indicating a growing preference for third-country purchases. As the previously mentioned YMTC investor noted, the second option after sourcing from China is "countries other than the U.S."[112]

China is increasingly redirecting business away from U.S. firms to non-U.S. foreign companies as part of its design-out strategy.

This trend, in part, reflects the unique limits the EAR places on U.S. firms compared to foreign companies. As previously discussed, companies can sell chipmaking equipment that U.S. companies—whose products are by definition "U.S. origin items"—cannot. Although the United States worked trilaterally in early 2023 to convince the Netherlands and Japan to adopt new controls on advanced chipmaking technologies, these rules do not equate to U.S. controls.[113] Dutch and Japanese restrictions are less stringent than the EL (a regulatory concept they lack a close equivalent to) and do not list China as a country of concern, creating substantial coverage gaps.[114] Additionally, Dutch and Japanese companies can keep personnel on site in China. This servicing ability provides a source of revenue and is a comparative advantage in SME, as toolmakers typically deploy teams of servicers within customers' fabs.[115]

Even for technologies the EAR does not encompass, there are reports that Chinese fabs are selecting third-country suppliers over their U.S. competitors. This trend may owe, in part, to U.S. companies overcomplying for fear of unintentionally violating export controls. In the United States, companies such as Applied Materials have faced criminal investigations for alleged violations of export controls, so it is unsurprising that other firms (particularly smaller businesses) would want to avoid these risks, even at risk of overcompliance.[116]

More importantly, Chinese firms have started seeing U.S. suppliers as higher-risk options compared to third-country suppliers. Tightening U.S. export controls has created a perception in Chinese markets that U.S. suppliers are not a reliable long-term procurement solution.[117] Chinese fabs are concerned both about the repercussions of violating existing controls—either knowingly or unknowingly—and mitigating exposure to stricter U.S. export controls in the future.[118] This view encourages Chinese fabs to turn to third-country toolmakers—at least until domestic supply develops sufficiently to avoid buying foreign technology altogether.[119]

This shift has both contributed to and been accelerated by growing efforts by third-country suppliers to win business away from U.S. competitors in Chinese markets—sometimes leveraging the U.S. export restrictions as a competitive advantage. In certain cases, industry participants described instances of foreign suppliers explicitly advertising their non-U.S. inputs (an indication they were not subject to the EAR) to attract new Chinese buyers or highlighting regulatory risks as reasons to select them over their U.S. competitors. For instance, some third-country firms raised concerns about future U.S. restrictions as reasons for Chinese businesses to choose them over U.S. firms.[120]

Industry events like SEMICON China 2024 also demonstrate the new competitiveness of third-country firms. Whereas U.S. firms were absent, other foreign sellers were not. Japanese tool firms, according to a report, kept a strong presence at SEMICON. Per the same report, Chinese demand for certain Japanese products is still strong, as Japanese companies have been rewarded with increased orders from Chinese firms, especially for noncontrolled products enabling leading-edge production.[121] This sales increase is apparent in Japanese trade data. Japanese exports of SME and related tools to China reached $3.32 billion in the first quarter of 2024, an 82 percent year-over-year increase.[122] There have even been reports that Japanese industry groups are arranging trips for Chinese chipmakers to explore "core opportunities in Japan's semiconductor equipment and materials industry," with a focus on getting around U.S. export controls.[123]

While CSIS has identified some preliminary evidence of third-country design-out taking place, there remains a shortage of publicly available data to estimate the extent of the phenomenon—specifically, detailed data from U.S. and third-country toolmakers on market share losses and gains in China. Some industry participants noted that U.S. and foreign companies hesitate to describe design-out trends due to concerns about investor perceptions. Even so, the trend represents the important and largely overlooked impact of increasingly broad and unilateral U.S. export controls that target China.

6

Chinese Firms Designing Around U.S. Firms in SME

SME has fewer examples of the design-around strategy–or innovating Chinese technologies to circumvent the need for U.S. technologies–compared to advanced packaging. This is, in large part, because the United States and allied countries have a strong lead over China in manufacturing chipmaking tools, making it harder for Chinese companies to develop innovations that sidestep or "leapfrog" U.S. capabilities in the space.

That said, one Chinese SME innovation bears mentioning in the context of design-around strategies. Increasingly, China is adopting new strategies to use older lithography equipment to achieve the same capabilities as EUV lithography, which represents a key chokepoint for Chinese lead-edge chip manufacturing.[124] EUV machines–exclusively produced by the Dutch company ASML–are considered essential to the production of advanced chips, and exports to China have been highly limited since the Dutch government imposed restrictions on EUV shipments in 2019.[125] However, in March 2024, Huawei and its chipmaking partner SiCarrier patented a technology known as self-aligned quadruple patterning (SAQP), which may allow them to produce the same chips as ASML's EUV machines in a novel way.[126] By using older DUV lithography equipment and additional etching to increase transistor density, China reportedly has the necessary capabilities for 5nm fabrication, an advancement beyond the 7nm process that SMIC provided for the Mate 60 Pro smartphone.[127]

Industry analysts believe China still needs EUV machines in the long run to reach 3nm capabilities–the leading edge in commercial production, as of this report, as pairing DUV with technologies like SAQP may represent a technological cul-de-sac in terms of achieving transistor density beyond 5nm.[128] As a result, China is also investing heavily in attempts to develop EUV lithography domestically via efforts by companies such as Naura and Huawei. These attempts to develop EUV represent an additional example of Chinese toolmakers designing out U.S. and allies' technology.[129]

7

Security Impacts of SME Controls

The effects of U.S. export controls on the SME industry will shape the future of U.S.-China strategic competition in semiconductors. Chipmaking tools are not only a key driver of advanced semiconductor capabilities but also an industry area where the United States currently leads in market share and innovation. According to 2022 estimates by the Semiconductor Industry Association and Boston Consulting Group, U.S. value-added activity made up 47 percent of the global SME market, along with 26 percent for Japan, 18 percent for the European Union, 3 percent for South Korea, and only 3 percent for China.[130] China is the largest importer of U.S. chipmaking tools in the world and is far from self-reliant.[131] It is reasonable that the United States would seek to use its leverage in SME to ensure leadership over its leading strategic competitor in a key dual-use technology.

However, current export controls could undermine the innovation leadership of the U.S. SME companies that created this leverage in the first place. The Trump and Biden administrations' efforts to control advanced chip capabilities have catalyzed a transformative shift away from U.S. technology in China but have failed to stop access to many controlled technologies due to widely documented smuggling efforts such as transshipments via third countries and domestic technology trading networks.[132] Moreover, policymakers have not reckoned with the fact that China's domestic semiconductor ecosystem is already making large strides toward replicating technologies previously supplied by U.S. toolmakers—aside from a few technological chokepoints, most notably EUV lithography.

Chinese—and to a lesser but still important extent third-country—toolmakers are poised to be the primary beneficiaries of China's ongoing shift away from U.S. chipmaking equipment. The primary losers of this transition therefore are U.S. toolmakers, who increasingly find themselves excluded from parts of the world's leading SME market. Importantly, the extent of this exclusion from Chinese markets is broader than that imposed by the export controls themselves due to multifaceted, interrelated trends such as Chinese companies hedging against future U.S. regulatory actions and overall declining trust in U.S. suppliers in Chinese markets.

In some cases, the financial impacts of export controls on U.S. toolmakers are already visible. The best available evidence of this trend is the previously mentioned April 2024 New York Federal Reserve study, which stated that export control announcements were associated with negative impacts on market capitalization and revenues for affected U.S. companies. Specifically, export controls preceded a 2.5 percent abnormal decline in stock price and an 8.6 percent decline in revenue.[133] Negative impacts on market capitalization have also taken place following the launch of criminal investigations related to export control violations. Shares of Applied Materials fell by as much as 8.3 percent following a November 2023 report that the company faces a criminal investigation regarding tools sold to SMIC. Shares of KLA and Lam Research also fell during the probe.[134]

The top-line growth of the Chinese market should not obscure the potential impacts of design-out on long-term U.S. SME revenues. Some U.S. toolmakers have seen growing sales to China because overall Chinese fab spending has soared in the last two years.[135] This short-term sales growth belies the underlying dynamic: market share is increasingly shifting toward Chinese and third-country competitors even as the market as a whole grows.[136] This trend will likely expand as Chinese firms like Naura and AMEC broaden their toolmaking capabilities. While the Chinese SME market "pie" is getting larger, the U.S. share is shrinking.

This decline in market share means the ultimate losers in the current export regime are U.S. economic and national security. SME markets are capital intensive and have fast-paced product development cycles, much like their foundry and integrated device manufacturer customers in the chip fabrication world. These features mean that market leadership historically has been concentrated among a small group of multinationals who are able to invest large sums in research and development and globalized manufacturing footprints. Lost revenues and market share can therefore have significant long-term effects on the ability of toolmakers to remain competitive in the future.[137] When U.S. SME companies are increasingly sidelined in Chinese acquisition of chipmaking technology, these same companies lose access to R&D dollars to support future innovation leadership.

Diminishing share in the Chinese market for U.S. toolmakers also means the U.S. government loses data on Chinese fab investment and technological capabilities. Historically, U.S. companies selling to China have offered a source of insight into China's semiconductor industry, particularly in terms of understanding the microelectronics capabilities available to Chinese defense and dual-use technologies. However, diverted market share to Chinese and third-country firms risks undermining this source of intelligence. The surprise release of Huawei's Mate 60 Pro in 2023 provides just one example of how Chinese semiconductor advancements increasingly take place under the radar of U.S. intelligence.[138] The risk of design-around innovation represents a particularly pressing concern, as increased Chinese innovation could result in novel technology advancements occurring without advanced U.S. awareness.

Imposing these export controls has clear costs for U.S. economic and national security. It is therefore worth considering ways the United States can achieve the benefits of export controls while minimizing costs.

8

Conclusion and Policy Recommendations

China's ongoing effort to reduce dependency on U.S. SME marks a significant change to previous Chinese industrial policy targets. Although China is still far from self-sufficient in chipmaking tools, its new trajectory represents an important step toward long-term semiconductor industry decoupling goals.[139] Increasingly broad and unilateral export controls are creating strong political and economic incentives for Chinese fabs to design out and around U.S. firms' technology, with important long-term implications for U.S.-China technology competition.

This trend is unlikely to reverse entirely, even if the United States relaxes export controls. China has demonstrated progress in developing SME capabilities and is likely to continue down this path. While Chinese indigenization achievements to date have focused on mature processes, future progress at the leading edge is increasingly likely for Chinese toolmakers.

Despite these changes, the United States can refine its export control regime to better balance national security and economic interests. A crucial step is to better understand how and where existing controls hurt U.S. companies. Conducting a survey of U.S. toolmakers through the Department of Commerce could provide valuable insights into market share shifts and competitive dynamics in global chip markets related to U.S. export controls. The survey could gather metrics like the share of Chinese tenders won by U.S. toolmakers relative to Chinese and third-country suppliers. It could also address the extent to which U.S. mature tools are being designed out, beyond the leading-edge tools that the controls target.

Past semiconductor industry feedback on Department of Commerce surveys has been mixed, with concerns about confidentiality and business sensitivity.[140] Therefore, the Department of Commerce must carefully communicate any new data collection efforts to ensure transparency and highlight the benefits for U.S. companies in shaping future export policies. If the survey provides evidence that current U.S. export controls have significant adverse impacts on U.S. toolmakers, the next step would be to consider how to mitigate these impacts. The current approach, which results in U.S. companies losing market share to Chinese and third-country competitors, is unsustainable—particularly considering how Chinese circumvention efforts arguably undercut the controls' national security objectives.

A key limitation of the existing controls is the failure of the United States to implement them multilaterally. Talks of a full trilateral agreement with the Netherlands and Japan reportedly broke down over inclusion of technologies such as memory and mature logic chips in controls on chipmaking equipment.[141] Any unilateral U.S. export control decision would fuel a growing view in Chinese markets that U.S. semiconductor companies are uniquely risky partners for Chinese companies—even relative to firms based in U.S. allies such as Japan and the Netherlands. The more the United States moves without allied support to control Chinese technology, the more it risks making its firms uncompetitive with allies' firms.

The United States must determine how to position its national security partners—not just Japan and the Netherlands but also South Korea, Germany, Israel, Taiwan, and potentially others—on more equal footing in terms of limiting trade of semiconductor manufacturing technologies with China. This strategy could involve a combination of the following three approaches:

1. Expand the application of FDPR and de minimis requirements within the U.S. controls to more effectively stop import substitution by third countries.
2. Apply increased economic or geopolitical pressure on allied countries to expand their own export controls.
3. Reduce the bounds of U.S. export controls to bring them back in line with multilateral agreements (e.g., the Wassenaar Arrangement).

The third option, by itself, seems highly unlikely. Any loosening of U.S. trade restrictions appears prohibitively challenging given bipartisan anxieties about China, particularly during an election year. The approach also could fail to stem Chinese companies' redirection of market share to third countries, as rolling back U.S. controls may not be enough to undo the loss of trust in U.S. firms within Chinese chip markets.

The U.S. government is focused on the first two options: (1) expanding the extraterritorial reach of the U.S. EAR and (2) convincing U.S. allies to implement more closely aligned controls. Expanding the FDPR and de minimis restrictions could limit sales of third-country technologies, but doing so risks further upsetting allies and accelerating efforts to remove U.S. technology and labor from third-country supply chains.[142] This trade-off limits the effectiveness of U.S. plans to add to FDPRs. The Biden administration is reportedly planning to expand the FDPR's product scope and add 120 new Chinese companies to the EL, effectively widening the EL FDPR's destination coverage. But, as previously mentioned, the rule is not expected to apply to category A:5 countries, which include the Netherlands, Japan, and South Korea, undercutting its effectiveness in limiting third-country exports of key chipmaking tools.[143] While an expanded FDPR would affect other countries and territories involved in chip supply chains, such as Israel, Singapore, and Taiwan, the impact on SME markets would likely be limited to specific niches or stages of fabrication.

The second option—greater multilateralization—is more promising. However, U.S. allies still have strong incentives not to impose restrictions that are comparable with the U.S. controls, as toolmakers are significant and influential economic actors in countries like the Netherlands, Japan, and South Korea.[144] To get around these obstacles, U.S. regulators should consider an expanded menu of carrots and sticks. The current strategy of appealing to shared national security concerns has clearly been unsuccessful. Allied governments have reportedly been unconvinced by justifications for the controls in terms of China's People's Liberation Army capabilities, in part because of very different perceptions among key partners (e.g., the European Union) of the extent to which China poses (or does not pose) a national security threat.[145] Some form of mutual benefit, such as via shared intelligence or economic opportunities, might therefore be necessary to convince allies to cooperate.

Regardless of what incentives are on offer, the United States likely must loosen some restrictions to achieve multilateralization. These reductions could focus on contentious areas such as memory chip production and nodes like 14nm and 16nm, which the semiconductor industry rarely considers "advanced." A narrower approach could better ground national security arguments for multilateralization, which resonate with allies for some technologies (e.g., tools for fabricating 7nm logic chips) more than others (e.g., tools for fabricating 128-layer NAND flash memory chips).

Loosening restrictions to enable greater multilateralization could be paired with efforts to improve enforcement of existing controls and stem circumvention efforts, which continue to blunt the controls' effectiveness at slowing China's technology development.[146] Combining these efforts provides one way to apply continued pressure on China's chip industry (and reduce domestic political pushback) while mitigating some of the controls' negative economic repercussions via greater cooperation with allies.

Finally, the United States, even if it does not pursue a loosening of the existing controls, could return to a strategic mindset of the "sliding scale" approach in designing future export control policy. This shift could help signal to the Chinese market that the United States is not pursuing full-scale decoupling of its technology ecosystem from China's and that it remains interested in doing business in technologies outside of the leading edge. This shift may be even more useful in convincing U.S. allies that U.S. companies will not be further restricted unilaterally and unpredictably from access to China's markets, helping secure their role as trusted and reliable participants in globalized technology supply chains.

Although U.S. toolmakers are key players in today's semiconductor markets, U.S. leadership did not develop in a vacuum and is not guaranteed indefinitely. China remains a critical and growing market for semiconductor fabrication, so export restrictions may have far-reaching adverse impacts on U.S. SME companies. If there is one recurring theme in writing policy related to semiconductors, it is that *details matter*. The U.S. government must take care to design future semiconductor export controls in ways deeply attuned to the nuances of semiconductor competitive dynamics, where one small change often has powerful ripple effects across global supply chains. Export controls must not jeopardize the complex web of factors underlying U.S. market leadership in semiconductors. Otherwise, the controls risk undermining the advantages the United States has in its important technology competition with China.

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