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Maintaining the AI Chip Competitive Advantage of the United States and its Allies

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AUTHOR
Saif M. Khan

I. Executive Summary

The United States and its allies enjoy a competitive advantage in the production of artificial intelligence chips necessary for leading AI research and implementation.[1] CSET has identified photolithography equipment as a key constraint in China's ability to manufacture leading edge chips with feature sizes of 45 nanometers and below.[2] Essential photolithography equipment is sold only by companies in the Netherlands and Japan, with related research and development in the United States. Coordinated export controls applied by these three countries on photolithography equipment—most importantly, steppers—could preserve U.S. and allied technological advantages and make China dependent for the near- to mid-range on imports of U.S. and allied chips for high-end AI applications. Key findings include:

- AI chips—highly specialized integrated circuits—are critical to quickly and efficiently train or deploy advanced AI algorithms.
- AI chip supply chains, especially the most high-value components, are highly globalized and concentrated in a small number of companies in a small number of countries.
- Photolithography equipment, which is dominated by Dutch and Japanese companies, is the primary choke-point in China's AI chip supply chain, while deposition, etching, and process control equipment, dominated by U.S. and Japanese companies, are secondary choke-points.
- China very likely will fail to build a competitive photolithography industry within the next decade due to its skilled labor shortfall, the technical complexity of the technology, and the monopolistic advantages of incumbents.

II. AI chips are critical for leading AI research and applications

AI chips are integrated circuits that are specialized and necessary to quickly and efficiently train or deploy advanced AI algorithms requiring significant compute power.[3] The cost of training a leading AI algorithm, such as Google DeepMind's AlphaZero, can run into the tens of millions of U.S. dollars even when using AI chips, but can cost orders of magnitude more with less advanced, less specialized chips. Likewise, performing inference using less advanced, less specialized chips may involve similar cost overruns and orders-of-magnitude slower operation, which is unacceptable for critical systems requiring fast real-time execution.[4]

III. AI chips supply chains are highly globalized and concentrated

The semiconductor supply chains for manufacturing leading edge AI chips are now globalized to such a degree that no country, including the United States and China, can make leading AI chips via exclusively domestic supply chains. Semiconductor industry sectors have localized in different regions based on the comparative advantages of those regions. Key sectors include: (1) basic research; (2) electronic design automation software used to design chips; (3) chip design; (4) semiconductor manufacturing equipment (SME); (5) materials providers; (6) semiconductor fabrication plants (fabs) that manufacture chips based on chip designs using SME and materials;[5] (7) assembly, testing, and packaging of manufactured chips; and (8) distribution of chips. The SME and fab sectors for leading node chips have consolidated into just a few companies in a small number of countries because of significant technical challenges and high costs limiting new competitors, combined with significant economies of scale.[6]

IV. Photolithography equipment is the key choke-point in China's AI chip supply chain

Compared to other semiconductor industry sectors, SME has a high degree of technical complexity and market consolidation. Three countries enjoy more than 90 percent market share, and six leading companies account for 78 percent market share.[7]

Table 1: Leading SME companies

Company	Applied Materials (U.S.)	Lam Research (U.S.)	KLA-Tencor (U.S.)	ASML (Netherlands)	Tokyo Electron (Japan)	Nikon (Japan)
Global market share[8]	18.8%	16.8%	6.4%	17.6%	16.7%	~2%
Revenue from China[9]	30%	16%	16%	15%	18%	28%

Photolithography tools, the most complex and expensive type of SME, are even more concentrated. ASML is the sole provider of extreme ultraviolet (EUV) photolithography tools, the most advanced photolithography technology, which is necessary for the manufacture of state-of-the-art 5 nm node chips (not yet in mass production) and even smaller future nodes. A single EUV machine costs more than $100 million. ASML also has a dominant market share in argon fluoride (ArF) immersion photolithography tools, the next most advanced photolithography technology, which is used for chips between the 45 nm and 7 nm nodes.[10] Nikon is the only other supplier of ArF immersion photolithography tools.[11] The United States has also played a key role in R&D for advanced photolithography equipment. Meanwhile, the United States and Japan are dominant in other advanced forms of SME, such as deposition, etch, and process control tools.

V. China is very unlikely to build a competitive photolithography industry

By comparison, China lacks a competitive SME industry and is unlikely to build one in the foreseeable future due to its poor resource allocation—a result of central planning—as well as its shortfall in skilled labor with necessary technical know-how,[12] and SME's extreme technical complexity. Industry consolidation favors incumbents, so China would need massive state subsidies to develop a competitive SME industry even if it attracted sufficient talent and efficiently deployed that talent and the requisite capital. A thorough assessment of the likelihood that China could achieve this goal requires further research,[13] but preliminary analysis suggests China is likely to remain reliant on U.S. and allied SME for at least the next decade.

VI. Limiting Chinese access to advanced photolithography tools would preclude China from establishing advanced semiconductor manufacturing capability

Although China has fabs, particularly Semiconductor Manufacturing International Corporation, with chip manufacturing capacity as advanced as the 14 nm node (as compared to the world-leading 5 nm node), China is dependent on the United States, the Netherlands, and Japan for imports of SME used to operate its fabs. Without access to advanced photolithography equipment supplied exclusively by the Netherlands and Japan, and advanced deposition, etching, and process control equipment supplied exclusively by the United States and Japan, China's domestic chip fabrication capacity would eventually become limited to, at best, the 90 nm node.[14] Leading-edge AI chips, however, are typically fabricated at the 16 nm node and smaller.

Coordinated export controls on China by the United States, the Netherlands, and Japan for EUV and ArF immersion photolithography tools would have complex positive and negative effects and side effects for the United States and its allies.[15,16] For example, while export controls may be attractive to limit China's capacity to produce advanced AI chips, they could also have undesirable consequences, including at least short-run loss of revenue for SME companies (see Table 1).[17] Such export controls may also lead SME companies to consider transferring operations to countries without export controls, as occurred in the case of U.S. export controls on satellites.[18] And export controls risk increasing tensions with China, which could choose to retaliate against the United States and its allies in a number of different ways. CSET will explore the complex dynamics of applying such export controls in a future report.

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Endnotes

[1] In this paper, AI refers to modern compute-intensive AI techniques, particularly deep learning.

[2] AI chips represent an archetypal technology following the logic of strategic dependency where "a concentration of foreign suppliers impose a negative externality for the importing state, represented by the potential economic and security costs of being cut off from accessing these items," where such assets have "low price elasticity" of both supply and demand, and "broad, ongoing flows." Allan Dafoe and Jeffrey Ding, "The Logic(s) of Strategic Assets" (forthcoming). Another model terms this dynamic "weaponized interdependence," where a state with political authority over central nodes of international networks designed to generate market efficiencies is deployed to choke off adversaries from economic and information flows. Henry Farrell and Abraham L. Newman, "Weaponized Interdependence: How Global Economic Networks Shape State Coercion", *International Security*, Vol. 44, No. 1 (Summer 2019): 42-79, https://www.mitpressjournals.org/doi/full/10.1162/isec_a_00351.

[3] Deep neural networks, a class of AI algorithms responsible for most recent AI breakthroughs, usually implement a type of machine learning called supervised learning, which involves two computing steps: "training" an AI algorithm based on training data (i.e. building the algorithm); and executing the trained AI algorithm (i.e. performing "inference") to classify new data consistent with what it learned about the training data in the training stage.

[4] General purpose computer chips like central processing units (CPUs) are suitable for a wide variety of computing tasks, whereas AI chips exhibit high speed and energy efficiency for training and inference of AI algorithms at the expense of energy inefficiency and low speed at other tasks. In this paper, the term "AI chips" refers to graphics processing units (GPUs), typically used for training, field-programmable gate arrays (FPGAs), typically used for inference, and application-specific integrated circuits (ASICs), typically used for both. Gaurav Batra, Zach Jacobson, Siddarth Madhav, Andrea Queirolo, and Nick Santhanam, "Artificial-intelligence hardware: New opportunities for semiconductor companies" (McKinsey, January 2019), Ex. 6, https://www.mckinsey.com/industries/semiconductors/our-insights/artificial-intelligence-hardware-new-opportunities-for-semiconductor-companies.

[5] Also called "foundries" when providing contract manufacturing services to third party design firms.

[6] Neil Thompson and Svenja Spanuth, "The Decline of Computers As a General Purpose Technology: Why Deep Learning and the End of Moore's Law are Fragmenting Computing", *SSRN* (December 12, 2018):32-35, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3287769; John VerWey, *The Health and Competitiveness of the U.S. Semiconductor Manufacturing Equipment Industry* (Washington DC: U.S. International Trade Commission, July 2019), 5-6,

https://www.usitc.gov/publications/332/working_papers/id_058_the_health_and_competitiveness_of_the_sme_industry_final_070219checked.pdf.

[7] International Trade Administration, *2016 Top Markets Report Semiconductors and Semiconductor Manufacturing Equipment* (U.S. Department of Commerce, 2016), 1, https://www.trade.gov/topmarkets/pdf/Semiconductors_Executive_Summary.pdf.

[8] Robert Castellano, “Semiconductor Equipment Revenues To Drop 17% In 2019 On 29% Capex Spend Cuts”, *Seeking Alpha*, March 27, 2019, https://seekingalpha.com/article/4251198-semiconductor-equipment-revenues-drop-17-percent-2019-29-percent-capex-spend-cuts.

[9] These percentages are based on CSET analysis of shareholder reports, which provide country revenue for the companies as a whole, not just for their SME businesses.

[10] EUV tools could also be used to fabricate chips at nodes within this range. Peter Clarke, “ASML increases dominance of lithography market”, *eeNews Analog*, February 12, 2018, https://www.eenewsanalog.com/news/asml-increases-dominance-lithography-market; Robert Castellano, “Canon's Nanoimprint Lithography: A Chink In ASML Holding's Armor”, *Seeking Alpha*, March 19, 2019, https://seekingalpha.com/article/4249762-canons-nanoimprint-lithography-chink-asml-holdings-armor.

[11] Robert Castellano, “ASML's Dominance Of The Semiconductor Lithography Sector Has Far-Reaching Implications”, *Seeking Alpha*, January 23, 2018, https://seekingalpha.com/article/4139540-asmls-dominance-semiconductor-lithography-sector-far-reaching-implications.

[12] Based on CSET analysis and consultation with experts, missing technical know-how (i.e. implicit knowledge acquired via learning-by-doing) is the critical bottleneck preventing China from achieving parity with the United States in the semiconductor industry, as compared to access to products for reverse-engineering, blueprints, or funding. It remains unclear, however, how long it might take China to acquire the requisite technical know-how if China made a concerted effort to acquire such knowledge either by importing it or via learning-by-doing.

[13] CSET is researching this issue in greater depth by reviewing the history of how Taiwan and Japan established themselves in the semiconductor industry, the literature addressing the development of complex industries, and a quantitative analysis of China's current access to talent, funding, and other elements essential for the creation of a competitive semiconductor industry.

[14] A Chinese company called SMEE is now developing 90 nm photolithography tools, although there is little evidence that SMEE’s tools are commercially viable at scale or technically reliable. “Current Status of the Integrated Circuit Industry in China”, *J. Microelectron. Manuf.*, Vol. 2, No. 19020105 (March 29, 2019): 6, http://www.jommpublish.org/p/26/.

[15] The U.S. Commerce Control List and the Wassenaar Arrangement already list photolithography equipment for feature sizes of 45 nanometers and below, but licenses are

often granted. Commerce Control List, Supplement No. 1 to Part 774, Category 3, 38-39 (May 23, 2019), https://www.bis.doc.gov/index.php/documents/regulations-docs/2334-ccl3-8/file. A new regime could instead deny most or all license applications for exports to China for controlled SME technologies by designating these applications for "presumptive denial," as is applied for many companies on the entity list, such as Huawei. However, if the Netherlands does not participate, the United States and Japan could instead multilaterally apply export controls on other forms of SME, such as certain types of deposition, etching, or process control equipment, in which they are dominant.

[16] Export controls could be imposed for chips at nodes equal to and smaller than either 45 nm or 65 nm. Applying export controls to chips at nodes larger than 65 nm (e.g., 90 nm) increases the risks of import substitution, given China's work on 90 nm photolithography tools (see footnote 14). Additionally, the security benefits of precluding Chinese fabs from fabricating 90 nm node AI chips is low, as these chips are dramatically slower and less efficient than leading node AI chips.

[17] Even if only photolithography export controls are applied, firms selling complementary SME could see sales losses as well, as China would have no use for that complementary SME. Moreover, EUV tools may reduce the role of other equipment such as etching and process control equipment, so U.S. SME companies may already face a revenue squeeze in the absence of export controls. Robert Castellano, "ASML's Dominance Of The Semiconductor Lithography Sector Has Far-Reaching Implications", *Seeking Alpha*, January 23, 2018, https://seekingalpha.com/article/4139540-asmls-dominance-semiconductor-lithography-sector-far-reaching-implications.

[18] Bureau of Industry and Security Office of Technology Evaluation, *U.S. Space Industry 'Deep Dive' Assessment: Impact of U.S. Export Controls on the Space Industrial Base* (Washington DC: U.S. Department of Commerce, February 2014), 15 and 28-39, https://www.bis.doc.gov/index.php/documents/technology-evaluation/898-space-export-control-report/file.