Is the EU's Semiconductor Manufacturing Equipment a Strategic Chokepoint?

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ABSTRACT

This chapter examines the critical role of lithography in semiconductor manufacturing and China's ongoing challenges in achieving technological self-reliance in this domain amid expanding European and US export controls. The paper outlines China's dependency on European lithography equipment, notably from Advanced Semiconductor Materials Lithography (ASML), and the concerted efforts by Chinese entities to develop indigenous capabilities, which have so far seen limited success. Despite significant investments and a strategic national push for import substitution, China's semiconductor manufacturing equipment industry, particularly in lithography tools, remains several generations behind its foreign counterparts. The analysis identifies systemic inefficiencies and limited synergies within China's lithography ecosystem, which will potentially continue to impede the development of competitive domestic lithography systems. The paper advocates for enhanced cooperation and alignment with Europe's allies, focused on promoting research to ensure Europe remains at the forefront of lithography innovation and thus indispensable to China's ambitions in semiconductor technologies.

SCORECARD 1 TECHNOLOGY FIELD: LITHOGRAPHY FOR SEMICONDUCTOR FRONT-END PRODUCTION

Source of European technology strength	Research and innovation	Intellectual property and patents	Production and commercialisation
	High	High	High

Type of European technology strength	Technological excellence	Commercialisation advantage	Conditioning of market access	Regulatory, political and normative factors	Sustainability	Research partnerships with third countries
	X	X				X

Degree of European leverage: Low – Medium – **High**

INTRODUCTION

In the 1970s, the US government had already identified export controls on semiconductor manufacturing equipment (SME) as an effective approach to controlling the transfer of "manufacturing know-how".[1] More than 50 years later, this is still a key objective of the United States and several allied governments. The US has reportedly been negotiating with Japan and the Netherlands at least since 2020, outside of multilateral export control forums such as the Wassenaar Arrangement, to expand their export controls on advanced SME to limit China's technological advancement in semiconductor manufacturing.[2]

1 US Department of Defense, "An Analysis of Export Control of US Technology: A DoD Perspective", 4 February 1976, accessed 10 April 2024, at https://apps.dtic.mil/sti/pdfs/ADA022029.pdf

2 Reva Goujon, Lauren Dudley, Jan-Peter Kleinhans and Agatha Kratz, "Freeze-in-Place: The Impact of US Tech Controls on China", Rhodium Group and Stiftung Neue Verantwortung, 21 October 2022, accessed 10 April 2024, at https://rhg.com/research/freeze-in-place/

For a long time, the Chinese government has been aware of the dangers that stem from its semiconductor industry's dependence on foreign-made SME. Even discounting earlier Chinese efforts to achieve import substitution in the semiconductor supply chain, since the mid-2000s the *02 Special Project for Integrated Circuit Manufacturing Equipment and Complete Processes* has sought to systematically reduce China's dependence on foreign inputs for semiconductor manufacturing.[3]

Various entities received support to conduct R&D and implement it in industrial production, selected according to what was supposedly a "targeted, competitive and merit-based approach".[4] In theory, this was a coordinated national effort drawing on China's historically state-administered research and development (R&D) complex and led by state fiat rather than market demand. The goal was to indigenise front-end semiconductor fabrication at progressively increasing levels of sophistication.

Two decades on, however, verifiable results in SME that are useable in industrial production under commercial conditions are still lacking. The basic problem is that SME development seems often to have been fragmented and not connected to real world production. Entities charged with developing various components and systems have done this under laboratory conditions, with limited interaction with other supply chain actors, especially the fabrication providers that are the end-users of SME.

This situation has persisted despite increasing state efforts to impose centralised coordination on the development of China's semiconductor industry. In 2014, China's State Council released the *National Integrated Circuit Industry* Development Outline, which tried to improve policy coordination and implementation by establishing a *Leading Small Group* (national steering committee) with support from an advisory expert committee.[5] Made in China 2025 was launched in 2015, accompanied by a technology roadmap from the Chinese Academy of Engineering that set relatively specific targets for the semiconductor industry, including on manufacturing equipment. The *IC Industry Technical Innovation Strategic Alliance* was established in 2017 to better coordinate research and innovation with industrial applications, again with a focus on semiconductors, including manufacturing equipment. Following the US export controls introduced in late 2022 to restrict China's access to foreign-supplied SME, a new Leading Small Group was reportedly established in early 2023 "to revamp high-level oversight [and] oversee all aspects of China's new strategy for the semiconductor industry".[6]

Despite all these top-down initiatives, China's fabrication plants (fabs) still depend heavily on foreign-made manufacturing equipment. China's domestic equipment suppliers are several technological generations behind their foreign competitors in a number of critical types of SME.[7] This, however, should not come as a surprise, mainly for two reasons.

First, Chinese semiconductor suppliers, such as Semiconductor Manufacturing International Corporation (SMIC), Yangtze Memory Technologies (YMTC) or ChangXin Memory Technologies (CXMT), do not face the same capital constraints as foreign competitors, due to the various levels and types of support they receive from the government.[8] Until recently, therefore, they were able to focus on catching up with their foreign competitors in terms of production capacity and finished products, including in the latter's technological sophistication: SMIC as a foundry[9] to the Taiwan Semiconductor Manufacturing Company (TSMC) and Samsung; YMTC in non-volatile memory chips (NAND) to Samsung and SK Hynix; and CXMT in volatile memory chips (DRAM) to Micron, Samsung and SK Hynix.

3 John Lee and Jan-Peter Kleinhans, "Mapping China's Semiconductor Ecosystem in Global Context: Strategic Dimensions and Conclusions", Stiftung Neue Verantwortung and MERICS, 30 June 2021, accessed 10 April 2024, at https://www.stiftung-nv.de/sites/default/files/chinas_semiconductor_ecosystem.pdf

4 Dongxing Securities, "关于北京华卓精科科技股份有限公司 首次公开发行股票并在科创板上市申请文件 审核问询函的回复" [Reply to the inquiry letter: Review of Beijing Huazhuo Jingke Technology Co., Ltd.'s application documents for initial public offering of shares and listing on the Science and Technology Innovation Board], accessed 10 April 2024, at https://pdf.dfcfw.com/pdf/H2_AN202206271575136026_1.pdf

5 Ibid.

6 Paul Triolo, "A New Era for the Chinese Semiconductor Industry: Beijing Responds to Export Controls", in *American Affairs 2024*, accessed 10 April 2024, at https://americanaffairsjournal.org/2024/02/a-new-era-for-the-chinese-semiconductor-industry-beijing-responds-to-export-controls/

7 Jan-Peter Kleinhans and John Lee, "China Semiconductor Observatory: Baseline Report 2022", China Semiconductor Observatory, 13 December 2022, accessed 10 April 2024, at https://www.stiftung-nv.de/sites/default/files/cso_baseline_report_2022.pdf

8 Organisation for Economic Co-operation and Development, "Measuring Distortions in International Markets: The Semiconductor Value Chain", 12 December 2019, accessed 10 April 2024, at http://dx.doi.org/10.1787/8fe4491d-en

9 A semiconductor foundry is a contract chip manufacturer that produces chips designed by their customers.

To achieve this, Chinese fabs needed best-in-class, that is foreign-made, SME. For several years, China has been the most important sales market, alongside Taiwan and South Korea, for foreign SME suppliers. In 2017, China accounted for 14.5% of equipment sales globally,[10] and it grew that share to more than 26% in 2022.[11] If instead Chinese fabs had prioritised utilising domestic equipment to assist the development of domestic SME suppliers, this would have jeopardised the competitiveness of Chinese fabs.

Second, especially in advanced semiconductor production, SME suppliers and fabs typically form relatively close relationships to constantly improve the production process and fine-tune the equipment.[12] Since domestic fabs preferred foreign-made SME, Chinese equipment suppliers had limited opportunities to learn from real-world high-volume manufacturing in order to improve their equipment. This only started to change significantly from around 2020, when Chinese chip manufacturers began increasingly to buy domestic equipment, at least for legacy chip production.[13] The revenues of Chinese SME suppliers have soared in recent years, not least due to the increased use of export controls on SME by foreign governments. The combined annual revenue of China's five largest SME suppliers, NAURA Technology (002371), Advanced Micro-Fabrication Equipment (688012), Piotech (688072), ACM Research (688082) and KingSemi (688037), grew from RMB 5.8 billion in 2018 to RMB 24.53 billion in 2022.[14] In other words, while the global SME market grew by 67% from US$ 64.5 billion in 2018 to US$ 107.6 billion in 2022, the sales of Chinese SME suppliers quadrupled. Notably, essentially all the sales by Chinese SME suppliers are to fabs in China.

With increased sales to Chinese fabs also comes closer cooperation between Chinese chip manufacturers and domestic SME suppliers, improving the competitiveness of Chinese SME suppliers in some types of equipment. One example is YMTC's reportedly close cooperation with Chinese etching equipment suppliers AMEC and Naura – driven by YMTC's specific targeting by US export controls since 2022.[15] One wafer fabrication equipment category where China's semiconductor ecosystem seems to have made little progress on decreasing its dependence on foreign, in particular European, equipment and components, however, is lithography.

CHINA'S DEPENDENCE ON EUROPEAN LITHOGRAPHY EQUIPMENT

In wafer fabrication, during the lithography process, light or electrons are used to transfer a pattern from a mask on to the surface of a (silicon) wafer, defining the intricate structures of the semiconductor devices. The Dutch lithography equipment supplier, Advanced Semiconductor Materials Lithography (ASML), currently has a monopoly on the most advanced type of lithography tools – extreme ultra-violet (EUV) scanners. Even for older types of lithography equipment, such as deep ultra-violet (DUV) immersion tools,[16] ASML has a quasi-monopoly, controlling more than 90% of argon-fluoride immersion (ArFi) tool sales globally, while Japan's Nikon accounts for the rest of the market: ASML sold 125 and Nikon nine pieces of ArFi equipment in 2023.[17]

To build its lithography machines, ASML relies on a network of 5000 suppliers, 200 of which ASML considers "critical".[18] Roughly half of those 5000 suppliers are

10 SEMI, "Semi Reports 2017 Global Semiconductor Equipment Sales of $56.6 Billion", 5 April 2018, accessed 10 April 2024, at https://www.semi.org/en/Global-Equipment-Sales-56-6-Billion

11 SEMI, "Global Semiconductor Equipment Billings Reach Industry Record $107.6 Billion in 2022, Semi Reports", 12 April 2023, accessed 10 April 2024, at https://www.semi.org/en/news-media-press-releases/semi-press-releases/global-semiconductor-equipment-billings-reach-industry-record-%24107.6-billion-in-2022-semi-reports

12 Jan-Peter Kleinhans and John Lee, op. cit.

13 Douglas Fuller, "Tech War or Phony War? America's Porous Controls on Semiconductor Fabrication Equipment and China's Response", 30 November 2023, accessed 10 April 2024, at https://www.prcleader.org/post/tech-war-or-phony-war-america-s-porous-controls-on-semiconductor-equipment-and-china-s-response

14 Authors' calculations based on companies' financial reports.

15 Qianer Liu and Cheng Leng, "Costs of US chip curbs force China's YMTC into major fundraising round", *Financial Times*, 2 November 2023, accessed 10 April 2024, at https://www.ft.com/content/4dcaaf91-d77f-4c70-97bf-69ba6a4e94f9

16 Also referred to as argon-fluoride immersion (ArFi) lithography equipment.

17 Nikon, "Financial Results for the 3rd Quarter of the Year Ending March 31, 2024", 8 February 2024, accessed 10 April 2024, at https://www.nikon.com/company/ir/ir_library/result/pdf/2024/24third_all_e.pdf ; ASML, "ASML 2023 Fourth-quarter and Full-year Results", 24 January 2024, accessed 10 April 2024, at https://www.asml.com/-/media/asml/files/investors/financial-results/q-results/2023/q4/presentation-investor-relations-q4-2023-m1ttie.pdf?rev=d95dae6ecb0f4abdaf87785af87eaa54

18 ASML, "Sourcing & Supply Chain", accessed 10 April 2024, at https://www.asml.com/en/careers/teams/sourcing-and-supply-chain

located in Europe but they accounted for 80% of ASML's supply spend in 2022.[19] ASML is best understood as a systems integrator. It builds only around 15% of the final lithography tool and most components are sourced from ASML's highly specialised supplier network, such as projection optics from Zeiss and EUV lasers from Trumpf, both German companies that are global leaders in their respective fields.

Thus, to achieve import substitution of lithography tools, it is not enough for China to simply strengthen the competitiveness of its domestic lithography tool supplier, Shanghai Micro Electronics Equipment (SMEE). SMEE, like ASML, depends on an ecosystem of component and subsystem suppliers for lenses, crystals, optics, lasers, wafer stages and much more. Based on recent data, in many cases these Chinese lithography component suppliers seem, in turn, to depend on foreign, including European, suppliers.[20] Thus, China's dependence on European technological strength in the lithography process extends substantially beyond ASML to suppliers of optical systems, lasers and many more technologies indispensable to advances in lithography.

ASSESSMENT OF DEPENDENCIES: HOW LITHOGRAPHY TOOLS ARE USED IN FABS

To assess China's past and future dependency on European lithography equipment, a variety of factors must be taken into account regarding the use of lithography equipment for wafer fabrication.

Fabs depend on all generations of lithography tools

Even cutting-edge 3nm process nodes for logic chips, such as smartphone processors, still use a mixture of DUV (KrF, ArF, ArFi) and EUV lithography tools.[21] Only certain areas of a chip depend on the most advanced lithography, while other functionalities have larger dimensions that can easily be built with older lithography technology. Since older generations of lithography tools are cheaper, less complex and tend to have a higher throughput (wafers per hour), fabs try to use them as much as possible. This is also the reason why ASML continuously releases new versions of its i-Line, KrF, ArF and ArFi tools.[22] Table 2 provides an overview of the different generations of lithography tools.

Process nodes can be built in different ways

Every fab has its own approach to combining different lithography generations in a new process node. For example, Intel, Samsung and TSMC built their first generation 7nm processes in very different ways: Intel's 7nm (equivalent) process utilised KrF, ArF and ArFi tools but no EUV; Samsung's 7nm process utilised KrF, ArF, ArFi and EUV tools; TSMC's 7nm process solely utilised KrF and ArFi tools, but neither ArF nor EUV tools were used.[23] Table 1 includes a likely estimate of SMIC's 7nm (N+1) process. Based on reputable analysis, it seems likely that SMIC's 7nm process is very similar to TSMC's first generation 7nm process. Since SMIC does not have access to EUV tools, it is likely that SMIC, just like TSMC, uses KrF and ArFi lithography tools for its 7nm process.[24]

TABLE 1: Type of lithography tools used in 1st generation 7nm processes

7nm	KrF	ArF	ArFi	EUV
INTEL	X	X	X	
SAMSUNG	X	X	X	X
TSMC	X		X	
SMIC	X	(X)	X	

19 ASML, "ASML Annual Report 2022", 31 March 2023, accessed 10 April 2024, at https://www.asml.com/en/investors/annual-report/2022

20 Eduardo Jaramillo, "China's Semiconductor Industry Can't Quit German Optics", The China Project, 1 May 2023, accessed 10 April 2024, at https://thechinaproject.com/2023/05/01/chinas-semiconductor-industry-cant-quit-german-optics/

21 ASML, "Investor Day 2021: Technology Strategy to Drive Moore 's Law into Next Decade", 2021, accessed 10 April 2024, at https://www.asml.com/-/media/asml/files/investors/investor-days/2021/asml-investor-day-2021-technology-strategy---martin-van-den-brink.pdf?rev=cc20a678382f45fdbf89ab69916b8478

22 ASML, "Investor Day 2021: DUV Products and Business Opportunity", 2021, accessed 10 April 2024, at https://www.asml.com/-/media/asml/files/investors/investor-days/2021/asml-investor-day-2021_business-line-duv---ron-kool.pdf?rev=eea4dec5c9384d48a21bb12f913aca90

23 Scotten W. Jones, "LithoVision 2020: Economics in the 3D Era", 2020, accessed 10 April 2024, at https://semiwiki.com/wp-content/uploads/2020/03/Lithovision-2020.pdf

24 TechInsights, "Comparing SMIC 7nm vs TSMC 7nm", 2022, accessed 10 April 2024, at http://nzz-files-prod.s3-website-eu-west-1.amazonaws.com/2022/08/30/ef873456-9644-4a36-b160-ec0d41853e68.pdf

TABLE 2: Different generations of lithography tools

LITHOGRAPHY TECHNOLOGY	POSSIBLE NODE DENSITY	FIRST USE	LIGHT SOURCE; WAVELENGTH	ASML	Nikon	Canon	SMEE
i-Line	350–220nm	~1985	Mercury vapor lamp; 365nm	X	X	X	X
KrF	250–80nm	~1990	Krypton fluoride (KrF) excimer laser; 248nm	X	X	X	X
ArF	130–38nm	~1998	Argon fluoride (ArF) excimer laser; 193nm	X	X		O
ArFi	40–7nm	~2005	Argon fluoride (ArF) excimer laser; 193nm	X	X		?
EUV	7nm–???	~2018	Plasma from tin droplet; 13.5nm	X			

Mixing lithography tools from different suppliers sacrifices accuracy

Even though Nikon is the only other supplier besides ASML to offer ArFi tools, its sales are minuscule. One reason is that fabs are reluctant to mix ArFi tools from different suppliers, since this substantially decreases the accuracy of the manufacturing process, negatively impacting yield. One self-described industry insider commented on X (formerly Twitter) that “this is how ASML is able to maintain its dominant market share for scanners. Nikon offers a perfectly good immersion scanner [ArFi tool] that, in some cases, performs better for overlay at an attractive price point. Despite this, an existing fab is reluctant to purchase one because of the performance impact against other ASML scanners in their fab”.[25]

Many different types of “auxiliary” tools are necessary for the lithography process

While everybody is aware of ASML’s dominance in lithography equipment, these machines depend on a variety of “auxiliary” equipment and consumables: ASML’s lithography tool shines light through (or on to) a photomask that holds part of the chip design. Transferring the chip design on to the photomask is done by mask writers, specialised lithography tools supplied by Austrian IMS Nanofabrication, among others.[26] The finished photomasks need to be checked for errors using metrology and inspection tools, such as those supplied by German Zeiss.[27] The wafer needs to be coated with photoresist, and after exposure the photoresist needs to be developed – all of this again using highly specialised equipment, for example from Tokyo Electron in Japan.[28] Mask blanks, mask writers, coater/developer tools, metrology and inspection tools, and photoresists are just some examples of critical tools and consumables indispensable to the lithography process.

Thus, to decrease their dependence on European lithography equipment, Chinese equipment suppliers would need to offer a range of lithography tools. Furthermore, fabs prefer to use ArFi tools from a single supplier to build advanced process nodes, since mixing these tools from different suppliers (i.e. ASML and Nikon) substantially reduces accuracy and yield. To gain insights from real world production, so that Chinese lithography tool suppliers can benefit from the experience and iteratively improve their equipment, Chinese equipment suppliers depend on fabs taking risks by using newly developed Chinese lithography equipment. If Chinese fabs are reluctant to take these risks and/or are under pressure to

25 X, Post from @lithos_graphein, 12 Feb 2024, accessed 10 April 2024, at https://twitter.com/lithos_graphein/status/1757130934648783337

26 Christof Klein and Elmar Platzgummer, “MBMW-101: World’s 1st High-Throughput Multi-Beam Mask Writer”, Photomask Technology 2016, accessed 10 April 2024, at https://www.ims.co.at/wp-content/uploads/2019/01/2016-10-17_BACUS-2016_IMS_MBMW-101_998505.pdf

27 Zeiss, “Photomask Metrology Solutions”, accessed 10 April 2024, at https://www.zeiss.com/semiconductor-manufacturing-technology/products/photomask-solutions/mask-metrology.html

28 Tokyo Electron, “Coater/Developer”, accessed 10 April 2024, at https://www.tel.com/product/act.html

ensure high yield and utilisation rates, Chinese lithography equipment suppliers will struggle to improve.

The latter dynamic in particular makes the competitiveness of SMEE, currently China's leading lithography machine systems integrator, of critical importance to China's prospects for achieving import substitution in lithography. The following section elaborates on what is publicly known about the current level of China's homegrown lithography tools.

ASSESSMENT OF DEPENDENCIES: THE COMPETITIVENESS OF SMEE

It is important not to conclude from Table 2 that Canon and SMEE are roughly at the same level technologically. Since 2020, Canon has sold between 120 and 180 i-Line and KrF tools each year, which is roughly four times more than Nikon.[29] Canon's equipment is used every day in high-volume manufacturing. In contrast, it is unclear how many of SMEE's i-Line and KrF lithography tools have been sold, let alone how many are being used successfully in high-volume front-end manufacturing.

In March 2023, the *Financial Times* quoted a manager of a Chinese chip supplier as saying that: "homegrown lithography [SMEE] was examined and verified by academics, not industrial engineers. This equipment is only theoretically usable, and no chip manufacturer has ever dared to activate such a machine in their fabs".[30] Such judgments are corroborated by detailed commentaries posted on Chinese social media from self-described industry insiders.[31] They also correspond with opinions shared with the authors by industry contacts. Since SMEE's lithography tools seem to be barely used by Chinese fabs, their technical specifications and performance on paper are ultimately of little relevance.

At the time of writing, SMEE's most advanced front-end lithography tool is the SSA600/20, an ArF-based tool supposedly capable of 90nm production. SMEE published the results of a performance test of a prototype of the SSA600/10 in 2011.[32] For comparison, ASML's PAS 5500/1150C, released for high-volume manufacturing in 2003, was ASML's first ArF-based lithography tool capable of 90nm production.[33] While SMEE has various (partially successful) lithography tools for display production and packaging, the company only advertises three tools for wafer fabrication: (a) the SSA600/20: ArF excimer laser at 193nm, capable of 90nm production; (b) the SSC600/10: KrF excimer laser, capable of 110nm production; and (c) the SSB600/10: i-Line mercury lamp, capable of 280nm.[34]

In recent years, there have been numerous media reports that SMEE would imminently be releasing a 28nm-capable ArFi (immersion) lithography tool, the SSA800-10W. It was initially reported the new ArFi-tool would be released at the end of 2021,[35] then by the end of 2022.[36] News again emerged that the SSA800-10W would be shipped by the end of 2023.[37] In December 2023, one of SMEE's state-owned shareholders posted a statement online that SMEE had successfully developed a 28nm lithography machine, but this was soon deleted

29 Authors' calculations based on companies' financial reports.

30 Qianer Liu, "China gives chipmakers new powers to guide industry recovery", *Financial Times*, 21 March 2023, accessed 10 April 2024, at https://www.ft.com/content/d97ca301-f766-48c0-a542-e1d522c7724e

31 EEWorld China, "马上2023了, 我国光刻机发展的怎么样了? [It's almost 2023: How is the development of photolithography machines in my country?], 15 December 2022, accessed 10 April 2024, at http://news.eeworld.com.cn/mp/EEWorld/a147909.jspx.

32 Lifeng Duan, Jianrui Cheng, Gang Sun and Yonghui Chen, "New 0.75 NA ArF scanning lithographic tool", SPIE, 22 March 2011, accessed 10 April 2024, at https://doi.org/10.1117/12.879376

33 ASML, "Reflect & Imagine: 20 Years of ASML, Chapter 5 1999–2004", 2004, accessed 10 April 2024, at https://www.chiphistory.org/exhibits/ex_se_asml_20yr_history/chapter5.pdf

34 Zhongtai Securities, "光刻机行业报告" [Lithography machine industry report], accessed 3 April 2023, at https://pdf.dfcfw.com/pdf/H3_AP202304061585172426_1.pdf?1680777189000.pdf ; SMEE, "SSX600系列光刻机" [SSX600 series lithography machine], accessed 10 April 2024, at http://www.smee.com.cn/eis.pub?service=homepageService&method=indexinfo&onclicknodeno=1_4_1_1

35 Toms Hardware, "China's 28nm-Capable Chip Fabbing Tool on Track Amid Trade War", 6 December 2020, accessed 10 April 2024, at https://www.tomshardware.com/news/chinas-28nm-capable-chip-fabbing-tool-on-track-amid-trade-war

36 Asia Financial, "China Expecting Key Native Lithography Machine this Year: SCMP", accessed 4 August 2023, at https://www.asiafinancial.com/china-expecting-key-native-lithography-machine-this-year-scmp

37 TechWire Asia, "China is Anticipating its First 28nm Lithography Machine by the End of 2023", 4 August 2023, accessed 10 April 2024, at https://techwireasia.com/08/2023/the-first-28nm-lithography-machine-in-china-this-year/?s=31

and replaced with a reference only to SMEE's commitment to developing advanced lithography machines.[38]

Industry observers are fairly sceptical about the real-world performance and production readiness of SMEE's latest tool: "Nothing has ever come of these reports in terms of equipment in mass production fabs. Instead, SMEE has created demonstration equipment in its laboratory".[39] Another industry observer states that the new SSA800 "is now likely part of a fully domestic production line that is being tested and certified", but it remains to be seen "whether SMEE can manufacture multiple commercial versions of the SSA800".[40] Thus, releasing a lithography tool that meets the technical specifications necessary for 28nm process nodes on paper is very different from that tool being successfully and widely used in 28nm high-volume manufacturing.

Even SMEE's older SSA600/20 90nm ArF tool seems to have no market relevance. As noted above, the company released performance tests of its SSA600/10 prototype (the predecessor to the SSA600/20) in 2011.[41] Around 13 years later, however, the machine seems to have had negligible sales.[42] It is reportedly not used by Chinese fabs for high-volume manufacturing. A significant amount of online commentary, including on Chinese social media, suggests that the SSA600/20 is not ready for use in production. At the time of writing, such commentaries suggested that only a handful of SSA600/20 have been sold to SMIC, YMTC, CXMT and other Chinese entities, none of which seem to use these machines for production.[43] One self-described industry insider (outside China) notes, that "only a few [SSA600] were shipped, so [SMEE] had no chance to make the incremental improvements needed to go beyond a subpar prototype".[44]

Another indicator that SMEE's SSA600/20 is not ready for commercial-scale wafer fabrication is ASML's growing equipment sales to China. ASML's net system sales to China grew from €1.54 billion in 2018 to €6.,36 billion in 2023.[45] Since 2019, based on SEMI data, at least 22 new fabs at 90–180nm (the intended application of SMEE's SSA600/20) were announced and/or had already started production in China.[46] It might be assumed that those Chinese fabs would eagerly source domestic lithography tools, but this does not seem to be the case. On the contrary, Nikon announced in November 2023 it would release a new i-line tool, which would be compliant with Japan's new export controls, specifically intended for the Chinese market.[47]

The apparent state of development of some of SMEE's component suppliers only reinforces the picture outlined above. For example, Beijing U-Precision Technology was established in 2012 specifically to conduct work on the 02 Special Project.[48] U-Precision has developed a dual wafer stage table for lithography equipment and supplies SMEE.[49] However, the compatibility of U-Precision's wafer table with SMEE's lithography machines has been questioned in the Chinese media.[50] This example is typical of the reported shortcomings of the siloed and

38 TrendForce, "Reports of SMEE Successfully Developing 28nm Lithography Machine, Original Source Deleted Shortly After", 22 December 2023, accessed 10 April 2024, at https://www.trendforce.com/news/2023/12/22/news-reports-of-smee-successfully-developing-28nm-lithography-machine-original-source-deleted-shortly-after/ ; and Lianhe Zaobao, „上海微电子据报成功研制出中国首台28纳米光刻机" [Shanghai Microelectronics reportedly successfully developed China's first 28nm lithography machine], 20 December 2023, accessed 10 April 2024, at https://www.zaobao.com.sg/realtime/china/story20231220-1457226

39 Douglas Fuller, "Tech War or Phony War? China's Response to America's Controls on Semiconductor Fabrication Equipment", 30 November 2023, accessed 10 April 2024, at https://www.prcleader.org/post/tech-war-or-phony-war-america-s-porous-controls-on-semiconductor-equipment-and-china-s-response

40 Paul Triolo, op. cit.

41 Lifeng Duan, Jianrui Cheng, Gang Sun and Yonghui Chen, "New 0.75 NA ArF scanning lithographic tool", SPIE, 22 March2011, accessed 10 April 2024, at https://doi.org/10.1117/12.879376

42 Douglas Fuller, op. cit.

43 EEWorld China, op. cit.

44 X, Post from @lithos_graphein on 12 Feb 2024, accessed 10 April 2024, at https://twitter.com/lithos_graphein/status/1757130934648783337

45 Based on ASML financial reporting

46 Based on SEMI World Fab Forecast Q4 2023, in 200mm equivalents.

47 Nikkei Asia, "Nikon Looks to Strike Gold in China's Low-tech Chip Device Market", 11 November 2023, accessed 10 April 2024, at https://asia.nikkei.com/Business/Tech/Semiconductors/Nikon-looks-to-strike-gold-in-China-s-low-tech-chip-device-market

48 Ibid.

49 Zhongtai Securities, "光刻机行业报告" [Lithography machine industry report], accessed 3 April 2023, at https://pdf.dfcfw.com/pdf/H3_AP202304061585172426_1.pdf?1680777189000.pdf

50 EEWorld China, op. cit.

bureaucratic approach to SME development of the past two decades, which as noted above has been criticised by Chinese commentators, including managers and officials quoted anonymously in foreign media.[51] Based on U-Precision's own Initial Public Offering (IPO) documents from Q3 2023, the company's wafer table system for ArFi lithography remains in development.[52]

In essence, there is a very long way between a breakthrough in lithography technology in the lab and the successful use of that tool in high-volume manufacturing. According to one self-described Chinese industry insider, the whole approach that Chinese industry and the authorities have taken to this challenge must change, his prescription being to concentrate equipment development on one "real" production line to systematically resolve problems and progress iteratively, with the initial goal being a useable 90nm lithography machine.[53]

ASSESSMENT OF DEPENDENCIES: RESEARCH AND DEVELOPMENT

There are indications that China's R&D-industrial complex is starting to adapt and to improve synergies between the disparate actors in its lithography development ecosystem. One study of China's lithography innovation network, based on patent data and published in 2023, assesses that the frequency of patent cooperation within the network is rapidly increasing, and that the network's size is growing by orders of magnitude through the addition of new nodes.

However, the authors conclude that the new nodes are often not well connected to the existing network, and that their addition is not translating into sufficient knowledge increase for the network as a whole. Accordingly, the network's "overall knowledge absorption capacity is poor". They recommend rebalancing the network's emphasis on "core" technologies by making more effort to integrate the development of supporting elements, such as photoresists and lithography gases. Improving coordination between the lithography innovation network and the policymakers shaping the institutional and development environment was also seen as important. Essentially, the authors advocate adopting ASML's model of an "open networked collaborative innovation paradigm".[54]

Similar conclusions have been reached even by authors writing within the ideological framework of "socialism with Chinese characteristics", and specifically about the "new-type national system" declared under Xi Jinping for mobilising and directing national resources for the development of strategic technologies like lithography. One commentator describes EUV's development outside China as based not just on resource accumulation, but also on international collaboration and "a clear profit distribution mechanism based on the market economy". He concludes that the "fundamental problem in perfecting the new-type national system", and thereby achieving breakthroughs in technologies like EUV, "is coordinating it with market forces and openness to the outside world".[55]

In summary, there is a very long way from breakthroughs in lithography-related technologies in the lab to successful use of a lithography tool in high-volume manufacturing. The evidence suggests that despite the long-term commitment of significant resources, China's lithography ecosystem has yet to resolve systemic inefficiencies and is some distance from being able to replicate the R&D model through which ASML developed advanced lithography. More specifically, there are various indicators to suggest that China's key lithography system integrator, SMEE, has yet to produce competitive lithography systems even for mature node wafer fabrication, let alone cutting-edge fabrication processes.

51 Qianer Liu, "China gives chipmakers new powers to guide industry recovery", *Financial Times*, 21 March 2023, accessed 10 April 2024, at https://www.ft.com/content/d97ca301-f766-48c0-a542-e1d522c7724e

52 Dongxing Securities, "关于北京华卓精科科技股份有限公司 首次公开发行股票并在科创板上市申请文件 审核问询函的回复" [Reply to the inquiry letter review of Beijing Huazhuo Jingke Technology Co., Ltd.'s application documents for initial public offering of shares and listing on the Science and Technology Innovation Board] , accessed 10 April 2024, at https://pdf.dfcfw.com/pdf/H2_AN202206271575136026_1.pdf; Zhongtai Securities, "光刻机行业报告" [Lithography Machine Industry Report], accessed 3 April 2023, at https://pdf.dfcfw.com/pdf/H3_AP202304061585172426_1.pdf?1680777189000.pdf

53 EEWorld China, op. cit.

54 GU Haoran, GUO Benhai, LONG Zhuoxi and LE Wei, "Evaluation and Optimization of China's Lithography Technology Innovation Network from the Perspective of Patent Cooperation", Industrial Engineering and Management", 2023.

55 Qu Guanqing, "The Historical Origin and Characteristics of the Times of the New National System: Also on the Research and Development of EUV Lithography Machines", *Journal of Hunan University of Technology*; (Social Science Edition), vol. 28, no. 6 (2023), pp. 7–14.

EUROPE'S AMBITION: CONTINUED CHINESE DEPENDENCY ON EUROPE

Because of the strategic relevance of decreasing its dependence on suppliers of foreign lithography tools, the Chinese government, chip manufacturers and the supplier ecosystem are eager to strengthen the competitiveness of their domestic lithography ecosystem. However, countless technological breakthroughs will be required. To that end, the Chinese government has reportedly given its leading semiconductor and equipment suppliers (Huawei, SMIC, YMTC, Naura and AMEC) privileged access to government R&D.[56] Importantly, strengthening China's domestic equipment ecosystem, including lithography, is no longer just a government effort. For example, Huawei's venture capital (VC) arm Hubble Investment invested in at least 107 companies between 2019 and 2024, the majority of which are within the semiconductor ecosystem.[57] Among these companies is RSLaser, controlled by the Microelectronics Institute of the Chinese Academy of Sciences, which is developing an excimer laser for lithography tools.[58] In November 2022, Huawei filed a patent on the EUV lithography process.[59]

It is hard to imagine a technology field of greater importance for China's policy goal of self-reliance. This makes it hugely challenging to meaningfully forecast the likelihood of technological breakthroughs in lithography equipment and provide remotely robust timelines in terms of market penetration. Apart from the undivided attention of the Chinese government, leading semiconductor companies and China's VC ecosystem, several other aspects must be taken into account when trying to forecast the future competitiveness of China's lithography ecosystem.

First, SMEE and the wider Chinese lithography innovation ecosystem now know that what they need to achieve is technologically possible and feasible, making it easier to focus R&D efforts. This is especially true in the case of EUV, which was met with huge scepticism and substantial uncertainty regarding the feasibility of the approach early on.[60]

Second, it is not just about SMEE anymore. Chinese industry and government now realise that SMEE might not be their best bet for building production-ready lithography tools. There is now a flurry of activity in China's semiconductor equipment ecosystem as established SME suppliers, such as Naura and AMEC, reportedly kick-start lithography research.[61] Like other efforts in China's semiconductor ecosystem, Huawei seems to be playing a role in China's advances in lithography technology.[62]

Third, Chinese researchers and companies already have access to foreign DUV tools and can intricately study and reverse engineer them. The latter matters since SMEE's goal is not to compete with ASML, Canon and Nikon internationally, but simply to achieve import substitution for China's domestic chip manufacturing.

Fourth, no one benefits from open communication of technological breakthroughs. Neither the Chinese government, nor Huawei, SMIC or SMEE have any incentive to publicly announce concrete technological breakthroughs. It will become increasingly difficult to confidently assess China's technological capabilities, especially in "weaponised" chokepoint technologies such as lithography tools.

56 Paul Triolo, op. cit.; Gregory Allen, "In Chip Race, China Gives Huawei the Steering Wheel: Huawei's New Smartphone and the Future of Semiconductor Export Controls", 6 October 2023, accessed 10 April 2024, at https://www.csis.org/analysis/chip-race-china-gives-huawei-steering-wheel-huaweis-new-smartphone-and-future

57 PitchBook, "Hubble Investment", accessed 10 April 2024, at https://pitchbook.com/profiles/investor/432600-22

58 SMM, "Huawei's Latest Investment in Lithography Machine to Understand the List of Domestic Industry Chain", 7 June 2021, accessed 10 April 2024, at https://news.metal.com/newscontent/101498347/huaweis-latest-investment-in-lithography-machine-to-understand-the-list-of-domestic-industry-chain

59 DigiTimes, "Huawei Confirms Breakthrough in EUV Lithography Process Optimization", 26 December 2022, accessed 10 April 2024, at https://www.digitimes.com/news/a20221226VL203/euv-huawei.html

60 ASML, "Making EUV: From Lab to Fab", 30 March 2022, accessed 10 April 2024, at https://www.asml.com/en/news/stories/2022/making-euv-lab-to-fab

61 Che Pan, "Tech War: China Quietly Making Progress on New Techniques to Cut Reliance on Advanced ASML Lithography Machines", *South China Morning Post*, 1 April 2024, https://www.scmp.com/tech/tech-war/article/3257442/tech-war-china-quietly-making-progress-new-techniques-cut-reliance-advanced-asml-lithography

62 Yuan Gao and Debby Wu, "Huawei Tests Brute-force Method for Making More Advanced Chips", Bloomberg, 22 March 2024, accessed 17 April 2024, at https://www.bloomberg.com/news/articles/2024-03-22/huawei-tests-brute-force-method-for-making-more-advanced-chips; and Cheng Ting-Fang, "Huawei Building Vast Chip Equipment R&D Center in Shanghai", Nikkei Asia, 11 April 2024, accessed 17 April 2024, at https://asia.nikkei.com/Business/Tech/Semiconductors/Huawei-building-vast-chip-equipment-R-D-center-in-Shanghai#

Fifth, most lithography tools are not impacted by export controls. For i-Line, KrF and ArF tools, SMEE will have to continue to compete with ASML, Canon and Nikon in the Chinese market.[63] Here, it will probably continue to be challenging for SMEE to gain market share in China. Whether a Chinese fab, operated by an IDM or a foundry, will continue to source older DUV tools from foreign market leaders or SMEE is likely to depend on a variety of factors. Chinese companies on the US Entity List, for example, would probably prefer to largely depend on domestic suppliers. Of course, the story is different for advanced ArFi and EUV tools, the export of which is controlled by the US, the Netherlands and Japan.[64] Here, entirely Chinese-made tools are the only option for Chinese fabs.

Sixth, lithography depends on many auxiliary tools and materials in which China would also need to establish competitive suppliers to become fully self-reliant. While this paper's analysis concentrates solely on lithography exposure tools (stepper/scanner), the above-mentioned mask blanks,[65] mask writers,[66] photoresist coater/developer,[67] among several others, are also indispensable to the lithography process. In many of these technologies and materials, European, Japanese and US companies are among the market leaders in often highly concentrated markets.[68] As noted above, Chinese researchers have recently assessed that the lithography innovation ecosystem still gives too little emphasis to such supporting elements.[69]

Finally, continued sourcing from foreign Tier 2 and Tier 3 suppliers will speed up SMEE's efforts. SMEE and its domestic component suppliers would probably achieve production-ready lithography tools more quickly if they did not source solely from domestic technology suppliers but continued to rely on foreign Tier 2 and Tier 3 suppliers.[70]

Against this backdrop, the following assessment of the likelihood of SMEE (or another Chinese lithography system integrator) building production-ready tools should be treated with due caution.

How likely is it that by 2035 SMEE (or another Chinese lithography system integrator) will have a substantial market share in China using entirely Chinese-made lithography equipment?

- It is *highly likely* that entirely Chinese-made *i-Line tools* will have a *substantial market share* domestically by 2035.
- It is *very likely* that entirely Chinese-made *KrF tools* will have *meaningful market shares* in China by 2035. KrF lithography tools will still be important for memory chip (NAND and DRAM) production at that time.[71]
- It is *likely* that entirely Chinese-made ArF tools will have *successfully entered the Chinese market* by 2035. Since SMEE already has an ArF-based system with the SSA600/20, it seems to be only a matter of time until the company improves the tool enough to make it capable of commercial-scale wafer fabrication.
- It is *unlikely* that Chinese-made ArFi tools will have *meaningful market shares* in China by 2035. For that to happen, Chinese-made ArFi tools would need to: (a) be capable of commercial-scale throughput (wafers per hour) and reliability; (b) have the necessary overlay accuracy (dedicated chuck overlay)[72]

63 Reva Goujon and Jan-Peter Kleinhans, "All In: US Places a Big Bet with October 17 Controls", 6 November 2023, accessed 10 April 2024, at https://rhg.com/research/all-in/

64 CSIS, "The Post-October 7 World: International Perspectives on Semiconductors and Geopolitics", 28 September 2023, accessed 10 April 2024, at https://www.csis.org/analysis/post-october-7-world

65 A mask blank in lithography is an unpatterned, precursor substrate used for creating photomasks, which contain parts of the design of the chip.

66 A mask writer is a specialised, highly precise lithography tool that transfers the chip design on to the mask blank.

67 Equipment to apply, develop and remove the photoresist on the wafer.

68 SemiAnalysis, "Austria's Silent Monopolies on Advanced Semiconductor Manufacturing: EV Group and IMS Nanofabrication", 24 August 2022, accessed 10 April 2024, at https://www.semianalysis.com/p/austrias-silent-monopolies-on-advanced

69 Gu Haoran, Guo Benhai, Long Zhuoxi and Le Wei, op. cit.

70 Eduardo Jaramillo, op. cit.

71 ASML, "Technology Strategy to Drive Moore 's Law into Next Decade: ASML Investor Day 2021", 2021, accessed 10 April 2024, at https://www.asml.com/en/investors/investor-days/2021. Since China's YMTC and CXMT cannot depend on US tools to upgrade and expand their fabs, there should be ample opportunity for SMEE to serve China's memory chip fabs – if their KrF tools are reliable and perform.

72 Reva Goujon and Jan-Peter Kleinhans, op. cit.

to allow for complex multi-pattering processes to achieve ≤14nm production; and (c) be based on a fully domestic supplier ecosystem. Thus far, only two companies in the world have achieved this: ASML and Nikon, both with unrestricted access to a global supplier ecosystem.

- It is *highly unlikely* that an entirely Chinese-made EUV tool will have achieved *production-readiness* by 2035. It took ASML and its suppliers the best part of three decades to achieve that and, at the time of writing, there does not seem to be a viable alternative approach.[73]

Lastly, when looking at the more abstract level at Europe's technology strength, or better that of ASML and its suppliers, it becomes clear that it plays out across all three dimensions:

- **Research and innovation:** ASML has a long-standing R&D collaboration with imec, the leading research and technology organisation (RTO) for front-end process and transistor development.[74] However, ASML also has very close R&D partnerships with its customers, such as TSMC,[75] as well as its peers, and suppliers of auxiliary lithography equipment, such as Tokyo Electron in Japan.[76] The amount of research collaboration that ASML conducts across its entire ecosystem – from its own component and material suppliers, to other equipment suppliers and customers – has directly contributed to ASML's success.[77] Such ecosystem-spanning, collaborative R&D is one of Europe's strengths but also very much dependent on company culture and not easily built-up from scratch. That said, SMEE would not necessarily need to follow ASML's approach. Nikon and Canon are much more vertically integrated successful lithography companies. As described above, however, Chinese commentary often emphasises lack of cross-ecosystem cooperation as the key impediment to the lithography import substitution effort.

- **Patents and intellectual property (IP):** ASML, together with German optics supplier ZEISS SMT, controlled more than 750 EUV patent families as of December 2021: "Their combined family count exceeds the sum total of the next 9 ranked players combined. [...] EUV lithography is one of the most consolidated patent landscapes imaginable. This is a reflection of task complexity and the fact that the ASML/Zeiss partnership have effectively side-lined their historical competitors, Nikon and Canon".[78]

- **Commercialisation and production:** As mentioned above, whereas Nikon and Canon are substantially more vertically integrated, ASML is best understood as a system integrator, building just around 15% of the lithography tool itself. This requires a tremendous amount of knowledge not just about every single physical aspect of the tool itself, but also about the challenges of high-volume wafer fabrication and how it is deployed in a fab. As shown above, having a lithography tool that meets technical specifications on paper is very different from successfully operating lithography tools in high-volume manufacturing. ASML is not just selling tools anymore but providing critical services to fabs. The company generates around 30% of its revenue from service and maintenance contracts.[79]

In conclusion, Europe's strength in lithography technology is equally rooted in R&D, patents and IP, as well as the commercialisation and production of the tools. Thus, Europe's technology aspiration should be to further develop European technology strength.

73 SemiEngineering, "Nanoimprint Finally Finds its Footing", 20 April 2023, accessed 10 April 2024, at https://semiengineering.com/nanoimprint-finds-its-footing-in-photonics/

74 Techovedas, "How IMEC Made ASML the Biggest Company in Europe?", 21 August 2023, accessed 10 April 2024, at https://techovedas.com/imec-made-asml-the-biggest-company-in-europe/

75 TSMC, "TSMC and ASML Reach Agreement to Develop Next Generation Lithography Technologies as an Extension of Long-Term Partnership", 5 August 2012, accessed 10 April 2024, at https://pr.tsmc.com/english/news/1734

76 ASML, "Tokyo Electron Limited and ASML Announce Agreement", 30 November 2011, , accessed 10 April 2024, at https://www.asml.com/en/news/press-releases/2011/tokyo-electron-limited-and-asml-announce-agreement

77 Hiroyuki Chuma, "Increasing Complexity and Limits of Organization in the Microlithography Industry: Implications for Japanese Science-based Industries", Research Institute of Economy, Trade and Industry, March 2005, accessed 10 April 2024, at https://www.rieti.go.jp/jp/publications/summary/05030000.html

78 Mike Adel, "ASML's EUV Tool is not Just the Pinnacle of Chip Making: It is a Benchmark of IP Dominance", 28 December 2021, accessed 10 April 2024, at https://www.linkedin.com/pulse/asmls-euv-tool-just-pinnacle-chip-making-benchmark-ip-mike-adel/

79 ASML financial reports

QUALITY OF EUROPEAN TECHNOLOGICAL STRENGTH

This section briefly considers the extent to which Europe's strength in lithography technologies could be used as political leverage vis-à-vis China. The quality of Europe's technological strength differs according to lithography generation.

Ease of circumvention/replication

The broadened export controls on ArFi lithography tools introduced by the US, the Netherlands and Japan incentivise China's SME ecosystem to achieve complete import substitution in the longer term. Using another technology instead of lithography tools for semiconductor production, or *circumvention*, is not possible at the technology level, but it is possible at the tool level – at least to some extent: Chinese fabs could order ArFi tools for older process nodes but then use them for more advanced nodes;[80] or, through multi-patterning techniques,[81] existing ArFi equipment can achieve 7nm and potentially also 5nm process levels, allowing Chinese fabs to circumvent existing EUV controls at least in the short to medium term. However, going beyond 5nm fabs would require access to EUV tools.[82] Trying to control the use of advanced ArFi tools already exported to China would be challenging and partially explains why some Chinese fabs seem to have stockpiled equipment in recent years.[83] Replication, or reverse-engineering foreign-made equipment, does not seem to have been overly successful for SMEE in the past 20 years. That said, it would be naive to believe that replication efforts have not intensified in recent years linked to the US-China technology rivalry.

Spillover damage if used as a chokepoint

Exploiting Europe's strong position in lithography tools through export controls could be done in two ways: denying the export of new tools to China; and/or denying the export of spare parts and maintenance of already installed equipment in China. The latter would have a more immediate effect and a higher chance of spillover damage. Without spare parts, fabs would have to halt production, almost certainly in a matter of months. The effects would depend on the extent to which the fab relies on personnel from ASML for servicing and maintenance. If spare parts or servicing were denied through export controls, this could hypothetically disrupt the supply of chips to European end-customer industries.[84]

DISCUSSING EUROPE'S LEVEL OF AMBITION

The previous sections have made clear that Chinese fabs will very likely continue to depend on European lithography tools in the medium to longer term. However, it is also clear that China is painfully aware of this dependency and is working hard to strengthen its domestic lithography ecosystem. The following discussion of the four levels of ambition for Europe provides a structure for thinking through Europe's strategic options in (not) engaging with China.

- **Level 1: threat prevention.** The export of semiconductor equipment, such as certain types of deposition, epitaxy, etching and lithography equipment, has been controlled under the Wassenaar Arrangement (and by extension the EU's dual-use regulation) for many years. While semiconductor equipment has limited direct military utility, it is indispensable for the production of advanced semiconductors that, in turn, enable the technological upgrading of China's military. Thus, it is arguable that Europe's ambition, until the imposition of Dutch export controls on advanced DUV lithography equipment,[85] has been one of threat prevention at the very least.

- **Level 2: ability to deny.** If Europe's ambition is to use China's dependence on European lithography tools to deter it from acting against European

80 Paul Triolo, op. cit.

81 Multi-patterning, such as Self-Aligned Quadruple Patterning (SAQP), is a method for creating finer features on chips beyond the limits of current lithography technology. By repeating the lithography and etching process multiple times, multi-patterning allows for higher density chip designs using existing equipment.

82 SemiAnalysis, "China AI & Semiconductors Rise: US Sanctions Have Failed", 12 September 2023, accessed 10 April 2024, at https://www.semianalysis.com/p/china-ai-and-semiconductors-rise

83 Qianer Liu, "China on Cusp of Next-generation Chip Production Despite US Curbs", *Financial Times*, 6 February 2024, accessed 10 April 2024, at https://www.ft.com/content/b5e0dba3-689f-4d0e-88f6-673ff4452977

84 Jan-Peter Kleinhans and Julia Hess, "Understanding the Global Chip Shortages: Why and How the Semiconductor Value Chain was Disrupted", Stiftung Neue Verantwortung, 11 December 2021, accessed 10 April 2024, at https://www.stiftung-nv.de/sites/default/files/understanding_the_global_chip_shortages.pdf

85 Government of the Netherlands, "Government Publishes Additional Export Measures for Advanced Semiconductor Manufacturing Equipment", 30 June 2023, accessed 10 April 2023, at https://www.government.nl/latest/news/2023/06/30/government-publishes-additional-export-measures-for-advanced-semiconductor-manufacturing-equipment

security interests, export controls would be kept to a minimum. The goal would be to ensure that it continues to be easier for China to depend on EU lithography equipment than to successfully develop a domestic alternative. In that case, Europe's agenda would be focused on keeping China dependent, encouraging it to continue to use European lithography tools and discouraging technological disentanglement.

- **Level 3: ability to act.** This goal would go beyond discouraging China from technological disentanglement. If China accelerates the development of its domestic lithography ecosystem, Europe will need to incentivise European lithography equipment remaining several generations ahead of the Chinese competition. To that end, lithography-related R&D and most of the supply chain would need to continue to be in Europe.
- **Level 4: curtailment.** A curtailment strategy would essentially force China to develop its own lithography tools without relying on European IP, including at the level of subcomponents, making it as challenging as possible for China to achieve import substitution even in the long-term. This is arguably, at least to some extent, the intention behind expanding US export controls.[86]

POLICY RECOMMENDATIONS

A key challenge that Europe will continue to face in following through on its own ambitions is the US government's unilateral, extraterritorial application of its export controls from October 2023.[87] The US government imposed export controls on advanced lithography equipment (specific types of ArFi tools) using a 0% de minimis threshold. This means that the US government claims jurisdiction over *entirely foreign-made* lithography tools that meet certain performance thresholds if those tools are intended to be sold to China.[88] Even if a lithography tool contains no US components or IP, it still falls under US export controls if shipped to China from a third country. Thus, reaching a common understanding with the US government about "red lines" and thresholds would appear to be crucial.[89]

Furthermore, because of the increasingly expansive US export controls, China will continue to double down on import substitution in semiconductor technologies.[90] The emergence of a technologically competitive Chinese-made lithography tool will lead to dwindling market shares in China for foreign lithography tool suppliers. Thus, Chinese disentanglement in semiconductor technologies is directly incentivised and accelerated by US export controls. This development also makes it highly likely that, at least to some extent, China will be less dependent on foreign DUV lithography tools by 2035.

In conclusion, regardless of Europe's distinctive policy ambitions in connection with lithography tools, closer coordination with the US and Japanese governments regarding export controls on lithography equipment should be considered. The more nuanced and intricate European technology controls become, the better European policymakers need to understand the global competitive market and continuously assess foreign availability. This is a challenging and resource-intensive exercise. A better understanding of which ally grants technology licences in which cases and to what extent foreign availability is established is now crucial. Against this backdrop, the following recommendations mainly focus on *promote* and *partner* strategies, since a European *protect* agenda is currently constrained by the US government.

- **Level 1:** If Europe's ambition is threat prevention, it would be in contravention of the US government's and the Dutch government's export controls on lithography equipment.
- **Level 2:** At this level of ambition, Europe would limit the expansion of export controls on equipment to ensure that China has little incentive to develop its own lithography ecosystem. That said, with US, Dutch and Japanese export controls on lithography equipment in place, it is highly unlikely that China would see any reason not to double down on import substitution in the longer term.

86 Reva Goujon and Jan-Peter Kleinhans, op. cit.

87 Ibid.

88 Morgan Lewis, Navigating the New Export Maze: BIS Implements Additional Controls on Advanced Computing and Semiconductor Manufacturing Items, October 2023, accessed 17 April 2024, at https://www.morganlewis.com/-/media/files/publication/morgan-lewis-title/white-paper/2023/navigating-the-new-export-maze-bis-implements-additional-controls.pdf

89 Anh Nguyen, "The Discomfort of Extraterritoriality: US Semiconductor Export Controls and why their Chokehold on Dutch Photolithography Machines Matter", *European Journal of International Law*, 1 December 2023, accessed 10 April 2024, at https://www.ejiltalk.org/the-discomfort-of-extraterritoriality-us-semiconductor-export-controls-and-why-their-chokehold-on-dutch-photolithography-machines-matter/

90 Paul Triolo, op. cit.

- **Level 3:** If Europe wants to protect its ability to act vis-à-vis China through its dominance in lithography equipment, it will need to implement an R&D and industrial strategy focused on “running faster”, not just protect. [91] Since China is likely to master i-Line, KrF and ArF in the low to long term, Europe needs to ensure that its broader lithography ecosystem continues to innovate by deepening innovation cooperation with allies,[92] expanding R&D programmes and VC funding for start-ups, such as through the European Investment Bank’s accelerator programmes, and continuing to attract foreign talent and incentivise collaboration with foreign technology leaders, such as in South Korea, Japan and Taiwan.
- **Level 4:** Curtailing China’s advances in lithography tools would incur substantial economic losses for European companies and only accelerate China’s domestic ambitions. This would require export controls not only on tools, but also on components from European suppliers, potentially halting the servicing and maintenance of installed advanced ArFi tools in China,[93] as well as supporting European technology providers identifying IP theft in China.

SCORECARD 2 TECHNOLOGY FIELD: LITHOGRAPHY FOR SEMICONDUCTOR FRONT-END PRODUCTION

	Threat prevention	Ability to deny	Ability to act	Curtailment
Feasibility of level of ambition	Low	Low	High	High
Core policy recommendations	• Not aligned with current US extraterritorial export controls or Dutch export controls • Coordinate with US government to achieve a protect strategy solely focused on threat prevention (i.e. decrease restrictions on DUV equipment) • Incentivise pan-European R&D in lithography technologies through research frameworks, such as Horizon Europe	• Not aligned with current US extraterritorial export controls • Coordinate with US government to achieve a protect strategy focused on preventing China from acting against Europe’s security interests • Strengthen Europe’s indispensability in lithography technology through closer R&D with Japanese equipment and material suppliers; for example, through the EU-Japan Digital Partnership	• Incentivise continued entanglement with China’s equipment ecosystem to ensure use of European lithography systems (also consider cooperation with Chinese equipment suppliers) • Make it attractive for foreign technology suppliers to engage in R&D in Europe through R&D incentives, tax breaks, skilled migration regulation	• Coordinate with US and Japan on export controls on components for lithography systems • Scrutinize R&D collaborations in relevant research areas with Chinese companies and universities • Co-develop a research agenda and technology roadmap together with the US and Japan to bolster a highly integrated, transnational lithography ecosystem

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91 European Commission, European Economic Security Strategy, 20 June 2023, accessed 10 April 2024, at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023JC0020&qid=1687525961309

92 Julia Hess and Jan-Peter Kleinhans, “Chip Diplomacy”, 23 October 2023, accessed 10 April 2024, at https://www.stiftung-nv.de/sites/default/files/snv_chip_diplomacy_analysis_of_technology_partnerships.pdf

93 Karen Freifeld et al., “Exclusive: Targeting Chinese Chips, US to Push Dutch on ASML Service Contracts”, Reuters, 4 April 2024, https://www.reuters.com/business/us-urge-dutch-more-curbs-asml-chipmaking-equipment-china-sources-say-2024-04-04/