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Great Power Chokepoints: China's Semiconductor Industry in Search of Breakthroughs

"*Assaulting the fortress of key core technologies*" (打好关键核心技术攻坚战): the Chinese semiconductor industry may face wave after wave of technology transfer restrictions from Washington. In policy language, however, **the siege metaphor has a resolutely offensive connotation.** The term appears in the communiqué of the fifth plenum of the 19th CCP's Central Committee, in Xi Jinping's speeches, in expert commentaries and in opinion pieces. Can China's assault succeed?

The short answer is no: **a frontal assault is unlikely to succeed.** The castle is being increasingly fortified, barring easy access to an ever-expanding list of "key core technologies" for an ever-expanding list of Chinese buyers. Since the Trump administration initiated targeted measures against Huawei, US restrictive policies have both expanded in scope and gained in sophistication by targeting chokepoints more narrowly.

US policies seek to remain two to three generations ahead in design and manufacturing and limit the Chinese military's access to advanced semiconductor technology. These goals have been consistent in the semiconductor space, predating the Trump administration. But their evolving modalities and enforcement challenges reflect changes in the industry and in the level of urgency in Washington regarding China's catch-up. **Building an export control system capable of cutting the Chinese military's access to advanced AI chips is a current key US priority.** AI chips powering supercomputers are essential to conduct complex military simulations and weapons design. There would be some irony if China's purchase of US-designed AI chips enabled China to seriously challenge US superiority in battlefield awareness and operational planning – which the course of the war in Ukraine has once again highlighted.

Looking at recent developments in photolithography, EDA tools and AI chips, this paper argues that **chokepoints will withstand Chinese assaults if controls are strictly enforced.** This still leaves plenty of room for de-securitized business transactions with Chinese buyers. The most difficult challenge for an effective chokepoint policy is intangible technology transfers through education and research cooperation, and talent recruitment. Frontal breakthroughs suddenly removing chokepoints seem unlikely in the medium term, but **Chinese breakthroughs may happen in other innovative segments of the semiconductor industry, such as new materials and heterogeneous integration.**

1. China's breakthrough obsession

China's approach to fixing chokepoints strives for "breakthroughs" (突破). As Xi Jinping notes, ***"Key technologies are not gifted by others, and one can't always simply do as others do, one needs to strive for self-improvement and dare achieve breakthroughs"***. (核心技术不是别人赐予的); "*we must seize the opportunity, aim at the forefront of the world's science and technology, comprehensively upgrade our independent innovation capability, strive to achieve great innovation in basic technologies, and achieve major breakthroughs in key core technologies*".

A recently published book by three Chinese scholars, *Great Power Hurdles: How to Solve the Bottleneck Problem* (大国的坎:如何破解"卡脖子"难题) characterizes **bottlenecks as a natural law of international politics** – the leading power has always manipulated bottlenecks to slow down the catch-up of its near peer-competitor. Removing chokepoints in the semiconductor industry is more than an economic competition issue of unlocking China's potential to dominate the world's digital transformation. It is taken as an issue of grand strategy in China, seen from a US-China historical power transition perspective. This is about global leadership and the international order.

The authors of the book admit that **upgrading China's autonomous innovation capacity and removing bottlenecks is going to be a "long-term mission".** The heart of the issue is the need to adopt the right industrial policies to completely reshape China's semiconductor ecosystem. Their recommendations focus on financing, leveraging China's domestic market, and nurturing talent:

- Set up **specialized funds** to support the domestic growth of bottleneck technology players.
- Pursue a **chip nationalization policy** to leverage China's domestic market in telecommunication and energy networks, but also for China's public transportation and financial sectors.
- Establish a **national preferential policy** that encourages through financial incentives the incorporation of Chinese semiconductor technology in final products.
- Adopt a more effective **talent cultivation policy** by increasing the links between the industry and the education system, and enabling the participation of the industry in the design of the curriculums. This is not going to be an easy task, and the problem is worsening. China's Semiconductor Association estimates that China's skilled chip workers shortage exceeds 250000 this year, and could reach 300000 in 2025.
- Propose more attractive **incentives to recruit foreign talent**, such as an income tax break for highly skilled workers for a pre-defined period of time.

- Improve the living conditions for foreign workers in China - they particularly mention improving the "**political and cultural tolerance**" (提高政治和文化包容性).

It is unlikely that the race between China refining and intensifying existing industrial policies and the US tightening restrictive policies ends in the short term with a clear winner and a clear loser. In this offense-defense game, **the defense is better positioned to win if controls are meticulously enforced, but some loopholes exist.** In addition, the US is in the driver's seat, choosing the battles when designating new Chinese companies or adding new technologies on control lists - which leaves space for the Chinese semiconductor industry to achieve impressive progress in non-controlled areas.

2. The EDA battle begins

In August 2022, the Bureau of Industry and Security (BIS) of the US Department of Commerce issued **an order imposing a presumption of denial licensing regime to exports of a certain category of Electronic Design Automation (EDA) Software.** EDA tools are primarily known as design software enabling the conception of chips, but they also perform other functions. They validate the semiconductor manufacturing process to ensure performance; they are used to verify that the chip design corresponds to the requirement of the manufacturing process; and increasingly, they monitor and measure the performance of a chip after it is manufactured – a new growth area for back-end tools.

Until the August order, the US had not specifically targeted China's access to EDA tools. Hence, the decision could be a watershed moment. The Chinese semiconductor industry is extremely dependent on foreign EDA software. The market share in China of the three most advanced EDA software companies (Synopsis, Cadence and Siemens EDA) occupies more than 78% of China's domestic share – higher than their global market share of 70%.

The order targets the electronic computed-aided design needed to conceive gate-all-around field effect transistors (GAAFETs). This is a next-generation technology, covered by the Wassenaar Arrangement, and in several ways, is still in development. In Europe, the EU Chips Act specifically mentions the key importance of European R&D in that new space for miniaturization. GAAFETs are a chokepoint for design at the 2/3-nanometer (nm) node. More precisely, they enable scaling semiconductors to 3-nm and below, as an alternative to the FINFET architecture. Samsung announced the initial production of its 3-nm process node using GAA last June, and TSMC has stated to be moving to GAA designs for its 2-nm node, planned to enter production in 2025.

But **why did the US target GAAFETs, a new generation technology, when the most advanced Chinese foundry struggles with a 7-nm node prototype (see page 6, section 4 on photolithography)?** In IC design, some Chinese companies are operating at the 5-nm threshold, and others have recently achieved 7-nm technology.

- Alibaba formally unveiled its new 5 nm server chip Yitian 710 in late 2021;
- Baidu launched the mass production of its 7 nm AI chips Kunlun II in August 2021, aiming to develop the business applications of Baidu's cloud and edge computing in areas such as high-performance computing and autonomous driving.
- During the summer, Shanghai-based start-up Biren Technology announced the release of a general-purpose 7-nm GPU for application in big data and cloud computing.

But **this impressive progress relies on foreign EDA tools, and breakthroughs are out of reach for Chinese EDA companies.** China's 14th Five-Year Plan lists EDA tools as the first frontline semiconductor technology where China needs to achieve breakthroughs. Almost three decades after the launch of "Panda", the first Chinese-produced EDA suite, Chinese EDA companies (about 20 main players) still find themselves operating in a relatively closed ecosystem, cut off from the virtuous innovation cycle of the world's leading players. If a Chinese EDA company wanted to develop GAA design tools, it would need manufacturing requirements from TSMC and Samsung, and critical input from other key players in the supply chain, such as equipment providers, fundamental research units, etc. Developing a workable EDA solution needs to incorporate demands and feedback from a whole ecosystem of companies.

Empyrean, the most advanced Chinese EDA player which holds a 5.9% market share in China, only offers design solutions at 28nm. And like other players in the Chinese EDA ecosystem, Empyrean's products do not cover the full spectrum of EDA functions. **While companies have made progress in developing front-end solutions, they are not in the race for back-end software and are unable to market a full package of design solutions.** The authors of Great Power Hurdles estimate that Chinese EDA companies only cover 60% of EDA functions available on the market in their products.

A major hurdle to China's EDA industry is **talent cultivation and acquisition.** Here again, the problem is at the level of China's relatively closed domestic ecosystem. The three leading EDA companies are so technologically dominant that the decisive phase for talent cultivation is often after recruitment, rather than during years of academic formation. They have been excellent at attracting Chinese talent, and to some degree, help the progress of the Chinese industry. **Several Chinese EDA start-ups, such as Shanghai Hejian Industrial Software, Ame-**

dac or X-EPIC, were founded by returnees with a long experience in Synopsis or Cadence. Governments are not well equipped to prevent loss of talent. The Taiwanese government has developed regulations targeting intermediaries recruiting engineers and corporate staff. Earlier this year, Taiwanese law-enforcement agencies raided Amedac's Taiwan office on allegations that the company had been hiring semiconductor engineers from TSMC, violating regulations governing cross-strait relations. However significant and revealing these individual stories are, the scale of China's talent problem, and the fact that innovation takes place outside of China's domestic EDA ecosystem, means that **catch-up is not within reach.**

3. AI Chips, from Alibaba Cloud to the People's Liberation Army

But targeting GAA design tools is not only about creating a new barrier for the R&D of Chinese IC design companies. The move is one element of the **Biden administration's strategic decision to exploit China's dependence on US AI chips technology and target military end-users, to widen the military technology gap between the US and China.**

The immediate, visible commercial usage of 2-nm and 3-nm process nodes is the world's next generation of smartphones and personal devices. For instance, Apple just announced that its next-generation A17 chip, to be released in 2023, will use TSMC's 3-nm process. But the high performance of the most advanced chips will be key to the development of server capacity and supercomputers. Advanced machine learning systems able to process complex scenarios involving a large number of data or to model weapons systems need to be trained by cutting-edge chips.

In the race to dominate this segment of the semiconductor industry, the US is a clear front-runner thanks to the uncontested – and growing – superiority of US companies in IC design and EDA tools. But to ensure that the gap remains, strict export control is required. A Georgetown University study based on unclassified PLA purchasing data shows a clear record of Chinese military end-users acquiring US AI chips. This explains the Biden administration's sudden decision in August to ban the exports of AI chips to China produced by Nvidia and Advanced Micro Devices (top computing chips). **Since the ban will only be effective in early 2023, the decision led to a stockpiling race in China.** To meet the demand, Nvidia placed rush orders with TSMC for the manufacturing of the chips for its customers in China.

The ban completes the offensive on GAA tools, but it is soon to be followed by another set of restrictions targeting China's access to US-made AI chips, codifying the Nvidia/AMD decision, and **more restrictive action on chipmaking equipment to complicate the manufacturing of 14-nm node chips by Chinese fabs.**

Many in the semiconductor industry will ask whether military end-use is the real target, or only a side story hiding a move intended to preserve US competitiveness at the expense of its rising Chinese competitors. Indeed, the blurry limit between civilian and military uses of AI Chips means that the cloud and server businesses of Chinese giant companies, such as Baidu, Tencent and Alibaba, could be severely affected by the US decision. **The dilemma for the US export control authorities, when examining export license requests, will be to determine the end-use of the chip.** It is extremely uneasy to judge whether an advanced chip purchased by any Chinese company will, or will not, end up in a supercomputer simulating war operations.

4. Photolithography dilemmas: detecting where the weaknesses lie

Extreme ultraviolet lithography (EUV) has become the living symbol of chokepoint semiconductor technology. Since 2020, when the Dutch government declined to issue ASML an export license to sell the first EUV machine to Chinese leading contract foundry SMIC, the question has not been whether export licenses would be ever granted for EUV technology, but whether a stricter control approach would be adopted regarding earlier generations of lithography machines, such as deep ultraviolet (DUV), or a certain advanced category of DUV called immersion DUV.

The lack of access to EUV technology effectively blocks Chinese foundries three generations behind TSMC and Samsung, and favors Intel's catch-up vis-à-vis its Chinese competitors. The ban did not prevent SMIC from achieving prototype manufacturing of a 7-nm chip during the summer. However, rumors in the industry are that SMIC is only able to achieve a 15% yield using DUV (by comparison, TSMC's 7nm node process has a 70% yield) due to its high cost. If this is the case, mass production and viable commercialization are out of reach. But does it really matter? Yes, but only to some extent. In a market economy, low-yield manufactured at a dissuasive cost would deter any company from investing. In China, 7-nm mission-critical chips could still meet specific customer demands. As a prototype – "lab-level, not fab-level" according to researchers at Taiwan's Industrial Technology Research Institute (ITRI), **SMIC's 7-nm chip can find niche applications, including for the needs of the military.**

This state of affairs raises two questions.

First, is an export ban on DUV a solution to prevent access to 7-nm chips by Chinese military end-users? **This battle is already lost. Chinese fabs have stocked up DUV machines** made by ASML, Canon and Nikon, and **the likelihood that there are already DUV machines in**

use in Chinese military facilities is very high. Such a decision by the US would only undermine European and Japanese commercial interests with no clear military-relevant justification. As a reminder, from a European perspective, ASML spends 85% of its DUV procurement inside the European Union, with a deep supply chain including companies such as ZEISS, Heidenhain, Jenoptik, AEMtec, Exyte, and IGW. In addition, the manufacturing of advanced chips at the 7-nm node is a complex process for which DUV machines represent only one stage. Acquired Chinese DUV machines are certainly vulnerable to an interruption of maintenance services, but targeting other pieces of equipment, such as deposition and etch systems, is more likely to slow down China's military relevant catch-up.

Second, can China achieve photolithography breakthroughs? In the short term, it seems unlikely. China's leading company, Shanghai Micro Electronics Equipment (SMEE), has developed a prototype 90-nm photolithography tool, which has yet to generate sales and is in R&D phase for a 28-nm tool that would not support the Finfet process. Rather than banning sales of DUV machines, given the number of DUV machines on Chinese soil, **targeting the acquisition of components – optical instruments are a known weakness – is more likely to slow down SMEE's catchup.**

5. China's paths around the rising wall of restrictions?

Currently, China is not well positioned to achieve breakthroughs in EDA tools, advanced photolithography, nor to replace Nvidia and AMD's AI chips with domestic alternatives. If controls are enforced effectively, the existing gap between the Chinese and the non-Chinese ecosystem will be maintained, and even widened in some areas. However, **the Chinese semiconductor industry has three very promising growth areas.**

First, a widening gap is not in contradiction with China's growing relative importance as a manufacturing base for mature generations of semiconductors. The authors of *Great Power Hurdles* underline that in the past 4 years, China has built ten 12-inch wafer fabs, for a total investment of 320 billion RMB; that 14 new fabs are currently under construction, for a total investment of 510 billion RMB; and that 23 more are in the planning phase. Between September 2020 and November 2021, China's wafer capacity increase, almost exclusively mature fabrication capacity, accounted for 26% of the worldwide total. This increase in manufacturing capacity is unparalleled. Inevitably, **China is going to capture a higher market share in an expanding market for earlier generations of manufacturing nodes.** TSMC's $2.9 billion investment to expand its Nanjing fab to increase production of 28-nm generation semiconductors, targeting the needs of the automotive industry, epitomizes this trend. For mass production of mature nodes, China offers an extremely attractive ecosystem. This fundamental Chinese industrial power means that should a US-China war in East Asia take place, China will be less exposed than Russia to a sudden embargo of dual-use semiconductor technology. Unlike the Russian arms industry, which is desperately struggling to procure microelectronic components to replenish stocks, **China has credible domestic options to sustain a war effort against a semiconductor embargo, which would not hurt all Chinese weapons systems.**

Second, the Chinese industry is well positioned to achieve breakthroughs and economies of scale in new materials. As the authors of Great Power Hurdles argue, **new materials offer China an opportunity to "*overtake other cars on a bend*" (弯道超车), as most actors are approximately on the same starting line.** The market for power semiconductors on **silicon carbide (SiC) and gallium nitride (GaN)** substrates is set to triple by 2026, driven by the growth of electric vehicles. In 2020 alone, China invested in 25 projects in both SiC and GaN at a cost of $10.9 billion. The ongoing Chinese acquisition of British company Newport Wafer Fab, which may be blocked by the UK government under the National Security and Investment Act, is to a large extent about access to SiC technology. This segment of semiconductor technology, which constitutes a key growth space for leading European companies such as STMicroelectronics and NXP, is **not securitized by export control measures.**

Third, **Chinese players are well positioned to benefit from heterogeneous integration as a fast-emerging segment of advanced packaging.** Moore's Law has correctly predicted the path of miniaturization in the semiconductor industry, observing that the number of transistors in a dense integrated circuit would double about every two years. However, that is no longer the only paradigm in manufacturing as there are questions regarding foundry business below 2nm, in 1nm or even in Angstrom. This is where More-than-Moore comes in. Heterogeneous integration assembles various components with various functions in a System-in-Package, which can combine memory, sensors, processors, etc. The combination of functional components into a single composite device enables more complex and advanced functionality. It will find many industrial applications and unlock progress in the integration of the virtual and the physical worlds. The fact that the Chinese semiconductor industry is particularly competitive in the packaging segment is an advantage, even if global players such as TSMC, Intel and Samsung are able to invest more capital in heterogeneous integration research and development. Chinese companies like JCET and TongFu Microelectronics are engaged in fierce competition with traditional packaging players and the global foundry leaders, who seek to expand their market share in that space – this includes SMIC in China. According to ITRI researchers in Taiwan, **as heterogeneous integration is still an "embryonic field", with many players and thus a**

lack of concentration, specific technology transfer controls will not be effective. This is despite the fact that there are military applications to advanced packaging techniques.

6. US ambiguities and the future of allied coordination on technology transfers

The export control restrictions need to be examined against raw commercial facts. In October 2021, **the US Congress released documents showing a surprising number of export licenses granted for sales to two companies on the entity list of the US Department of Commerce:** 113 greenlighted for Huawei, worth $61 billion, and 188 for SMIC, valued at nearly $42 billion.

Overall, US sales of semiconductor technology to China have significantly increased across all segments of the industry in 2021. Qualcomm and Nvidia grew China sales by nearly $12 billion from 2020 to 2021, to about $29.6 billion. EDA sales by Synopsis and Cadence grew from $564 million in 2019 to $941 million in 2021. Sales of fab equipment by Applied Materials, Lam Research and KLA Corporation grew by 40% between 2020 and 2021, reaching $14.48 billion.

Of course, lists are not a ban - they impose a presumption of denial when examining export control licenses. But **the paradox is nevertheless obvious.** On the one hand, the Biden administration places additional restrictions on China's access to semiconductor technology on a quasi-monthly basis, with no sign of slowing down. On the other hand, the record shows that China's access to the US's leading companies is increasing in volume.

US restrictions on technology transfers are the result of a policy process involving the executive branch, resistance and lobbying by US companies, and a Republican opposition likely to soon take control of Congress, which has heavily criticized the administration for being too soft on designing and enforcing controls. **The net sum of those forces is that restrictions will only increase and become stricter, but the huge commercial interests of American companies in China will always hold important weight.**

The numbers give ground to those in Europe, Taiwan, Korea or Japan, who back the argument mentioned above: **US restrictions, on the surface, are about undermining Chinese Civil-Military Fusion's strategy, but in reality, they aim at creating competitive advantages for US companies at the expense of rival companies from allied countries.** From a European perspective, the semiconductor working group in the Transatlantic Trade and Technology Council, and the record of allied arms export control cooperation in response to the Russian invasion of Ukraine, have been positive developments, but the irritant has not disappeared.

There is no question that US executive action targeting Chinese military end-users will continue to generate collateral damage on purely civilian commercial transactions, which will hurt European and other business interests. The examples of GAA tools, photolithography and AI chips show how elusive military end-users can be to determine with certainty. The Chinese system of state capitalism here works against the interests of Chinese private internet companies. Who can conclude with certainty that an AI chip purchased by Tencent or Alibaba for their developing cloud and edge computing business will not end up in supercomputers operated by the People's Liberation Army?

There is no easy way out of this dilemma. Stopping China's progress at 5nm when it comes to design, 7nm when it comes to manufacturing, complicating Chinese companies' ability to operate below 14nm, and targeting military end-users, are four relatively clear policy goals. However, their implementation is a bureaucratic nightmare for licensing authorities, and export control is not enough.**China's breakthrough could come from domestic innovation spurred by the size of China's market if China can access sufficient human resources – and acquire foreign technology by any available means.**

7. Conclusion

Europe has enhanced its toolbox to prevent unwanted technology transfers. The numbers show that **only a tiny portion of EU-China trade and investment transactions is being "securitized"** by those defensive measures. In volume, this proportion will remain marginal but qualitatively, Europe has an interest in further improving its toolbox because a People's Liberation Army with greater access to cutting edge defense electronics increases the risk of war in East Asia. This analysis underlines **two areas where controls should be established: military-relevant heterogeneous integration, and talent recruitment.**

Addressing the challenges of heterogeneous integration could initially focus on EDA tools. Where should this start? 3D designing is an essential step for stacking. The leading EDA companies could be required to lock certain functionalities in the products they sell. It is worth noting that, with the Chips Act, the EU is **relaxing self-imposed restrictions preventing public support for industrial projects in the semiconductor industry.**

Talent conservation is a missing link in these stepped-up efforts to reduce European vulnerabilities in the geopolitics of technology. Taiwan, China's main target for talent poaching efforts, offers valuable early lessons. The Taiwanese Ministry of Economic Affairs is amending the *Regulations Governing the Permission of Establishing Branches or*

Agencies in Taiwan by Commercial Enterprise in the Mainland Area. The regulation intends to prohibit the setting up of research and development activities in Taiwan by subsidiaries or branches of Chinese companies. The Mainland Affairs Council is also proposing amendments to the provisions of the "Act Governing Relations between the People of the Taiwan Area and the Mainland Area". The amendments establish a review mechanism for travel by personnel engaged in core technology business receiving government support and increase penalties against proxy agents helping illegal Chinese investment in Taiwan. Since 2022, the Labor Ministry prohibits posting China-based jobs on Taiwanese platforms for critical sectors such as semiconductors. **Such moves aim to reduce outflows of human capital to the mainland, securing Taiwan's lead in the field.** The many specificities of cross-strait relations and of people-to-people relations across the Taiwan Strait should not lead to a fast judgment that Taiwanese policy experiences are irrelevant to European problems with talent conservation.

What should also be reminded is the insufficient weight placed on the links between semiconductor technology and defense innovation in Europe, with perhaps the exception of France, whose arms industry has created niches for local microelectronics. **A "trusted supply chain" is needed at the European level, and should not be limited to industrial players** - it should include civilian researchers at the origin of dual-use innovation.

Russia's war in Ukraine provides European policymakers with tangible examples of the importance of a resilient microelectronics supply chain to sustain a war effort, and conversely, of the extreme vulnerability of arms industries to foreign dependence. An uncompromising realism and a sense of urgency are needed in Europe to step up ongoing public policy efforts to **build a resilient military supply chain and insulate it from intrusions and technology captation by revisionist powers.**

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