ISSN (Print): 2788-8320 ISSN (Online): 2788-8339

JOURNAL OF SOCIAL RESEARCH DEVELOPMENT
www.jsrd.org.pk editor@jsd.org.pk

THE U.S.–CHINA SEMICONDUCTOR RIVALRY: EXPORT CONTROLS, CHINA'S TECHNOLOGICAL ADAPTATION, AND STRATEGIC IMPLICATIONS

Zaigham Abbas[1], Dr. Fouzia Amin[2], Major Ali Ahsan Hundal (Retd.)

[1]PhD Scholar, Strategic Studies, National Defense University/ University of Birmingham.
Email: zaighamabbas0@gmail.com, zaighamabbas0@outlook.com
[2]Assistant Professor, Strategic Studies, National Defense University. Email: fouzia@ndu.edu.pk
[3]MA IR from University of Balochistan. Email: aliahsan6690@gmail.com

KEYWORDS

U.S.–China competition; semiconductors; export controls; defensive realism; technological determinism; SAQP; SSMB-EUV; AI

ARTICLE HISTORY

Date of Submission: 07-10-2026
Date of Acceptance: 03-11-2026
Date of Publication: 04-11-2026

ABSTRACT

The U.S.–China technology rivalry has made semiconductors central to economic competition and national security. Washington has introduced export controls to restrict China's access to advanced computing chips and semiconductor manufacturing equipment. China has responded by investing in domestic fabrication, improving AI-software efficiency, expanding mature-node production, and exploring alternative technical pathways. This qualitative study examines these reciprocal strategies through defensive realism and technological determinism, drawing on government documents, industry reports, and technical literature. It evaluates self-aligned quadruple patterning (SAQP), the experimental steady-state microbunching (SSMB) EUV-source concept, silicon photonics, and carbon-nanotube devices without treating research progress as commercial maturity. The analysis argues that restrictions can constrain specific capabilities while also strengthening incentives for domestic substitution, thereby reshaping supply chains and strategic calculations. It recommends targeted, coordinated controls, stronger domestic and allied manufacturing capabilities, and sustained investment in emerging technologies and computing efficiency.

2026 Journal of Social Research Development

Correspondence	Zaigham Abbas
Email:	zaighamabbas0@gmail.com, zaighamabbas0@outlook.com
DOI	https://doi.org/10.59075/jsrd.v7i9.646
Volume/Issue	7(9), 2026, 271-301

Introduction: AI, Semiconductors, and Strategic Competition

Competition over advanced technologies has become a defining feature of the twenty-first century, with the United States and China seeking advantages in artificial intelligence (AI), 5G networks, industrial automation, and military innovation. Semiconductor chips are central to these applications because they enable computing, data processing, connectivity, and automated decision

support. Access to chip designs, manufacturing capacity, equipment, and supply chains therefore creates significant economic and strategic opportunities.

The United States has sought to restrict China's access to high-performance computing chips and selected semiconductor-manufacturing equipment. Controls adopted in coordination with partner governments have restricted China's access to advanced deep-ultraviolet (DUV) and extreme-ultraviolet (EUV) lithography equipment. At the same time, Washington has introduced domestic manufacturing incentives intended to reduce supply-chain vulnerabilities, especially those arising from geographic concentration of leading-edge fabrication in Taiwan.

U.S. semiconductor producers have cautioned that export restrictions may reduce revenues and encourage China to accelerate development of substitute technologies. These concerns do not establish that technological decoupling will necessarily succeed or fail; rather, they draw attention to competing effects. While controls can delay access to selected equipment and chips, sustained Chinese investment in local manufacturing could eventually diminish their leverage, including in AI applications.

China has responded through a combination of industrial investment, alternative fabrication processes, and improvements in computing efficiency. In addition to efforts to develop advanced chipmaking capabilities, Chinese firms are expanding mature-node production and using techniques such as mixture-of-experts architectures, dynamic computation and horizontal scaling to improve performance under hardware constraints. Chinese research institutions are also exploring advanced lithography, optical interconnects and novel transistor materials. These efforts collectively indicate a strategy of technological diversification rather than a single guaranteed route to self-sufficiency.

This paper investigates the trajectory of the U.S.–China semiconductor rivalry. It examines the intended effects and potential limitations of U.S. export controls; evaluates China's responses in industrial capacity, computing efficiency, and emerging technologies; and assesses the strategic and economic implications for Washington, Beijing, and allied supply chains. It concludes by proposing policy options that balance national security, industrial competitiveness, and long-term technological resilience.

Research Objectives and Qualitative Design

This study adopts a qualitative, theory-driven research methodology to examine the evolving U.S.–China semiconductor competition and its implications for technological power, national security, and global geopolitics. The study has four principal objectives: first, to examine the effectiveness of U.S. semiconductor export controls in restricting China's access to advanced technologies; second, to analyse China's countermeasures, particularly semiconductor self-sufficiency, software optimisation, alternative lithography, legacy-chip production, and emerging semiconductor technologies; third, to assess the implications of the competition for global semiconductor supply chains and U.S. allies; and fourth, to develop policy recommendations for maintaining U.S.

technological competitiveness while minimising unintended consequences of technology restrictions. The analysis is guided by Defensive Realism and Technological Determinism. Defensive Realism is used to explain the security motivations underlying U.S. restrictions and China's pursuit of technological autonomy, while Technological Determinism provides a framework for examining how technological advances may reshape economic, military, and geopolitical power.

Theoretical Framework

The U.S.–China semiconductor rivalry represents a complex intersection of geopolitics and technological advancement (Miller, 2022). Understanding this competition requires an integrated theoretical lens that accounts for both state behavior in an anarchic international system and the transformative role of technology in shaping global power dynamics (Jervis, 1978; Waltz, 1979). This paper integrates defensive realism and technological determinism to examine how security concerns shape state behavior, while technological advancements concurrently alter the balance of power (Bimber, 1990; Waltz, 1979). These theories provide a structured approach to understanding why semiconductor technology has become a strategic battleground and how state-imposed constraints and technological adaptation interact in shaping global competition (Miller, 2022).

Defensive Realism and Security-Driven Technology Policy

Defensive realism, a structural theory rooted in the works of Kenneth Waltz, posits that states, operating in an anarchic international system, prioritize security and self-preservation over unchecked expansion. States seek to balance against perceived threats, adopting measures to counter potential challengers that could disrupt the global power equilibrium. Waltz contends that while competition among states is inevitable, they tend to avoid unnecessary aggression that could weaken their strategic position, instead relying on deterrence, economic measures, and alliance-building to maintain stability.

The U.S.–China semiconductor rivalry can be understood through defensive realism because both governments frame access to critical technologies in terms of vulnerability and security. China's 2017 New Generation Artificial Intelligence Development Plan (AIDP) emphasizes AI applications in the economy, public services, and national defense and advocates military–civilian integration of scientific and industrial resources. That policy provides documentary evidence that China has long viewed AI as a dual-use strategic capability (Allen, 2019; Webster et al., 2017).

The military significance of AI is evident in its operational integration within the U.S. Department of Defense. Project Maven, launched in 2017, employs AI and computer vision to process surveillance imagery, identify objects of military interest, and support intelligence analysis and targeting. According to the National Geospatial-Intelligence Agency (NGA), Maven had more than 20,000 active users across over 35 military service and combatant command tools by May 2025. The agency also reported that Maven reduced targeting workflow timelines by as much as 80%, with one military exercise demonstrating a reduction from hours to minutes between sensing and target engagement (National Geospatial-Intelligence Agency [NGA], 2025). These developments

demonstrate the growing reliance of U.S. military operations on AI-enabled intelligence processing and decision support, reinforcing the strategic importance of advanced semiconductors and computing infrastructure.

China is similarly pursuing the integration of AI into military intelligence, operational planning, and command-and-control systems. A notable development is the **Tianji Military Large Model**, developed by Yuanting Technology, which incorporates generative AI into intelligence processing, operational planning, force allocation, and military decision support. The developer reports applications within Chinese military organizations, including automated military transportation planning, operational scenario generation, and risk assessment (Yuanting Technology, n.d.).

The growing military significance of generative AI is also reflected in several articles published in PLA Daily. Jia and Gu (2025) examined its potential applications in joint operations, including battlefield simulation, operational planning, and decision support. Similarly, Cai and Liu (2026) discussed how large language models could integrate multidomain intelligence, generate operational recommendations, and improve command-and-control coordination. Tian (2026) further emphasized the importance of developing indigenous AI capabilities and integrating them into air defence, intelligence assessment, operational coordination, and logistics.

Although these publications primarily articulate doctrinal priorities and prospective applications rather than independently verified combat deployments, they demonstrate the PLA's sustained interest in integrating AI into military systems. From a defensive realist perspective, these developments reinforce China's incentives to secure domestic semiconductor production and computing capabilities, particularly as U.S. export restrictions threaten access to advanced hardware essential for military AI development.

The U.S., perceiving China's rapid technological advancements as a challenge to its global dominance, has taken further export control measures to restrict Beijing's access to critical semiconductor technologies. These measures include:

- Export-control regulations on advanced computing chips and semiconductor-manufacturing equipment (distinct from the CHIPS and Science Act's domestic industrial incentives and the proposed SAFE Chips Act).
- Strategic alliances with key Lithographic equipment and semiconductor producing nations such as Japan, South Korea, and the Netherlands,
- Investment in domestic semiconductor industries to reduce reliance on global supply chains.

From a defensive realist standpoint, these policies reflect Washington's effort to preemptively block China from gaining technological parity in fields such as AI and advanced military applications. By restricting access to high-end semiconductor manufacturing tools, most notably Extreme Ultraviolet (EUV) lithography, the United States aims to preserve its strategic advantage and contain China's rise within the existing global order.

Conversely, China's response aligns with defensive realism's assertion that states, when faced with external constraints, will prioritize self-sufficiency to protect their national security interests. Viewing U.S.-imposed restrictions as an attempt to undermine its economic and technological sovereignty, China has intensified investments in domestic semiconductor manufacturing. Key developments include:

- Expansion of mature-node semiconductor production and potential supply-chain leverage.
- Addressing hardware handicaps with software innovation such as mixture of experts, dynamic computation, horizontal scaling etc.
- Investment in alternative fabrication routes and research-stage semiconductor technologies.
- State-led initiatives to advance silicon photonics and carbon nanotube-based semiconductors as potential alternatives to traditional chip fabrication.

Through mature-node expansion, software optimization, and research into alternative semiconductor technologies, China seeks to reduce exposure to external supply restrictions. These efforts may reshape the global competitive landscape, although their effects will depend on achieved production yields, industrial scale, cost, and access to complementary equipment and materials.

Technological Change and the Distribution of Power

Defensive realism explains the security concerns motivating the two states, while technological determinism highlights how advances in production and computing can alter economic and strategic choices. Technological determinism on the other hand, emphasizes the role of technological advancement in transforming social, economic, and political structures. Historically associated with debates concerning the relationship between technology and societal change, particularly the writings of Karl Marx, this perspective highlights how technological innovations can influence institutional development and the distribution of power. However, technological change does not independently determine national policies or geopolitical outcomes but interacts with political, economic, and social conditions to shape broader structural transformations.(Smith & Marx, 1994).

Semiconductors are foundational inputs for AI, digital infrastructure, communications, and many military systems. Their strategic relevance arises not only from commercial demand but also from their potential contribution to intelligence processing, decision support, surveillance, and precision systems. Accordingly, both states may treat dependence on foreign advanced-computing ecosystems as a security vulnerability rather than as an ordinary market condition.

Washington has sought to restrict access to selected advanced computing technologies while strengthening domestic fabrication capabilities. This policy reflects concerns about the military and intelligence applications of advanced computing, together with the desire to protect a long-standing technological advantage. Its effectiveness must nevertheless be assessed against market incentives, implementation challenges and the responses of suppliers and buyers.

From a technological perspective, China's efforts to develop indigenous computing capacity reflect the increasing importance of AI in military, intelligence and economic applications. Dependence on foreign processing hardware, design tools or fabrication equipment can create strategic risks. Export controls have therefore strengthened incentives for Chinese authorities and firms to invest in chip production, optimize compute-intensive workloads and establish a more autonomous AI ecosystem.

Technological determinism thus helps explain why semiconductor production has become central to U.S.–China strategic competition. AI capability depends on more than chip supply alone, yet hardware access materially affects cost, training scale, deployment, and military applications. Both states have incentives to diversify supply chains and reduce single-point dependencies. Within this framework, export controls and countervailing efforts toward self-sufficiency are interacting choices shaped by both strategic calculations and technological possibilities.

The Interaction of Security Competition and Technological Adaptation

While defensive realism and technological determinism provide distinct analytical perspectives on the U.S.–China semiconductor war, neither theory alone fully captures the complexity of this strategic and technological competition. The two frameworks must be understood as mutually reinforcing; state-imposed constraints influence technological trajectories, while technological advancements, in turn, reshape strategic calculations.

From a defensive realist perspective, the United States' restrictions on China's access to advanced semiconductor technologies constitute a preemptive security measure aimed at maintaining its technological dominance. Washington perceives China's progress in semiconductor innovation, particularly in AI and advanced chip fabrication as a direct challenge to its global leadership. Consequently, the U.S. has enacted export controls, supply chain realignments, and strategic alliances to contain China's semiconductor ambitions. These actions align with the realist assumption that states seek to prevent shifts in the balance of power that could undermine their security.

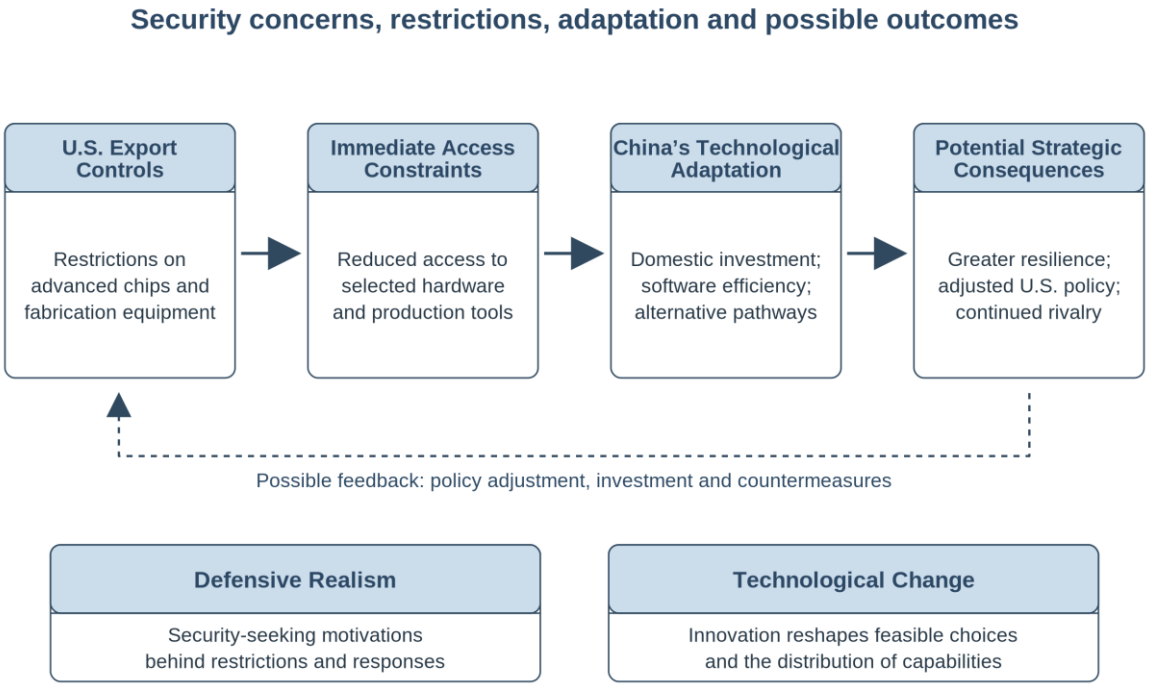
Technological change also alters the practical options available to policymakers. The interaction between security-driven restrictions and technological adaptation can be summarized as follows:

- The United States, seeking to prevent China's technological rise, imposes restrictions on semiconductor exports and supply chains.
- China, rather than being permanently constrained, responds by investing in domestic semiconductor capabilities, software innovations and novel chipmaking technologies reducing its dependency on Western suppliers.
- The resulting technological advancements reshape global power dynamics, compelling the United States to adjust its strategy, potentially tightening restrictions or accelerating its own semiconductor development efforts.

Thus, semiconductor competition is not merely a static geopolitical contest; rather, it is a dynamic and iterative process, where strategic constraints and technological adaptation continuously shape each other. The outcome of this rivalry will not be determined solely by which state controls existing semiconductor supply chains but by which actor can sustain long-term technological innovation, resilience, and adaptability.

Figure 1

Conceptual Framework of the U.S.–China Semiconductor Rivalry



Note. Author's conceptualization; arrows indicate a possible sequence and feedback, not a deterministic outcome.

Documentary Sources and Comparative Analysis

The research relies on primary and secondary documentary sources. Primary sources include U.S. and Chinese government documents, legislation, policy papers, executive actions, regulatory announcements, defence and budget documents, and official statements relating to semiconductor policy, export controls, AI, and technological development. Secondary sources include academic literature, research reports from institutions such as CSIS, CNAS and Rhodium Group, technical and

industry publications, and reports from reputable media organisations including Reuters, Financial Times, New York Times, South China Morning Post, and IEEE Spectrum. Sources were selected according to their relevance, credibility, authority and direct relationship to the research objectives. No primary survey or interview data were employed; the study therefore relies on documentary evidence and publicly available information.

The collected material was analysed through qualitative thematic and comparative analysis. Evidence was organised around major themes including U.S. export controls, China's semiconductor self-sufficiency, advanced and legacy chips, lithography, AI hardware, software efficiency, emerging semiconductor technologies, supply-chain dependence, and geopolitical consequences. The evidence was subsequently compared through the theoretical lenses of Defensive Realism and Technological Determinism to assess the motivations, responses, technological adaptations, and strategic consequences of U.S.–China competition. Particular attention was given to whether U.S. restrictions are achieving their intended objective or, conversely, creating incentives for China to accelerate indigenous technological development.

Research Limitations

The study has several limitations. First, it does not employ original interviews, surveys or field observations and therefore cannot directly capture the perceptions of policymakers, industry executives, engineers or military practitioners. Second, semiconductor technology is highly dynamic and information concerning advanced manufacturing capabilities, technological yields, and military applications is often commercially sensitive or classified. Consequently, some assessments of China's technological progress rely on publicly available evidence and contain inherent uncertainty. Third, several emerging technologies examined in the study, including SSMB-EUV, silicon photonics and carbon-nanotube-based semiconductors, remain at different stages of development, making their future strategic significance difficult to determine with certainty. Finally, because U.S.–China technological competition is ongoing, subsequent policy and technological developments may alter the trajectory identified in this study.

Findings and Discussion: Strategic and Economic Implications

The semiconductor rivalry affects international markets, technology investment, and security relationships. The following discussion considers both the direct effects of restrictions on advanced manufacturing and the broader adjustments among states, suppliers, and downstream users.

U.S. Export Controls and Global Supply Chains

Semiconductors are at the forefront of modern technological advancements, serving as foundational components of cutting-edge innovations that shape strategic competition in the twenty-first century. The United States, threatened by China's rapid advances in critical technologies, has attempted to limit its access to advanced semiconductor technology. On December 2, 2024, the United States launched its third major crackdown on China's semiconductor industry in three years,

imposing export restrictions affecting 140 companies, including chipmaking equipment manufacturer Naura Technology Group. The measures targeted nearly two dozen semiconductor companies, two investment firms and more than 100 chipmaking equipment manufacturers (Freifeld & Shepardson, 2024). Their primary objective was to restrict China's access to advanced semiconductor manufacturing equipment and technologies that could support AI, advanced computing, and military applications (Bureau of Industry and Security, 2024). Chinese Foreign Ministry spokesperson Lin Jian criticized the restrictions for disrupting international economic and trade relations and emphasized China's determination to protect its legitimate security and development interests (Ministry of Foreign Affairs of the People's Republic of China, 2024).

The restrictions also carry economic repercussions for U.S. allies, particularly Japan, South Korea, and the Netherlands, whose semiconductor industries maintain significant commercial relationships with China. For instance, approximately 30% of Samsung's high-bandwidth memory (HBM) sales were estimated to originate from China when the December 2024 restrictions were announced (Freifeld & Shepardson, 2024). Similarly, ASML, the world's leading manufacturer of extreme ultraviolet (EUV) and deep ultraviolet (DUV) lithography equipment, has been prohibited from exporting EUV and certain advanced DUV lithography systems to China. The Chinese market accounted for approximately 49% of ASML's revenue during the first half of 2024, reflecting its considerable dependence on Chinese demand (Teng, 2024). However, amid tightening export restrictions and broader concerns about semiconductor demand, ASML's shares plunged by approximately 24% during the third quarter of 2024. Although ASML was not directly affected by every U.S. restriction, broader market speculation about a bearish trend in the semiconductor industry encouraged investors to withdraw funds from semiconductor stocks. Its net bookings subsequently declined to €2.6 billion in the third quarter of 2024, compared with approximately €5.6 billion in the preceding quarter, falling considerably below market expectations (ASML, 2024). The company initially anticipated that China's contribution to its total revenue would decline to approximately 20% in 2025, compared with approximately 29% in 2023. However, its subsequently reported China revenue share for 2025 was 29.1%, illustrating that Chinese demand proved more resilient than initially anticipated (ASML, 2026).

The U.S. semiconductor industry also faces financial risks from restrictions on sales to China. Nvidia, the leading American manufacturer of graphics processing units (GPUs), disclosed in 2023 that sales of products affected by licensing requirements to China and other restricted destinations had accounted for approximately 20–25% of its data-center revenue in preceding quarters. The company anticipated a significant decline in sales to these destinations following the imposition of additional export controls (NVIDIA Corporation, 2023). Earlier, in May 2023, Nvidia's chief executive, Jensen Huang, warned that restrictions on China's access to American chips could ultimately encourage Chinese companies to manufacture competing technologies domestically (Murgia et al., 2023). These developments suggest that U.S. semiconductor restrictions may generate economic repercussions not only for China but also for American companies and allied semiconductor manufacturers.

The controversy surrounding semiconductor exports has continued to influence U.S. legislation. On December 4, 2025, a bipartisan group of senators, led by Pete Ricketts and Chris Coons, introduced the SAFE Chips Act, proposing restrictions on the export of advanced AI chips to foreign adversaries, including China. The proposed legislation would require the U.S. Department of Commerce to deny relevant export-license applications for at least 30 months, while strengthening congressional oversight of semiconductor exports (Office of Senator Pete Ricketts, 2025). Four days later, President Donald Trump announced that Nvidia would be permitted to export its H200 AI chips to approved Chinese customers, subject to national security conditions and a 25% payment to the U.S. government. Although, the H200 remains a highly capable processor, it belongs to Nvidia's older Hopper architecture, while the more advanced Blackwell and forthcoming Rubin architectures were excluded from the authorization. The decision reflected Washington's attempt to balance national security considerations with economic interests by preserving American semiconductor companies' access to the Chinese market and discouraging Chinese customers from shifting toward domestic alternatives such as Huawei. The administration's approach nevertheless attracted criticism over concerns that advanced American processors could accelerate China's military and technological capabilities (Nellis et al., 2025).

Nevertheless, several loopholes remain in the U.S. semiconductor restrictions that China may exploit. To address shortages of advanced AI-processing chips, China's response has encompassed four principal strategies (Wang, 2024):

- Stockpiling substantial quantities of advanced AI chips before export restrictions took full effect.
- Enhancing domestic semiconductor manufacturing capabilities through state investments, technological innovation and upgrades to indigenous fabrication processes.
- Procuring restricted chips through third-party channels, notwithstanding applicable export controls.
- Leveraging offshore AI computing and cloud services to reduce direct dependence on restricted semiconductor imports.

These measures illustrate that restricting China's access to advanced semiconductors does not necessarily eliminate its ability to develop AI capabilities. Rather, such restrictions may encourage Beijing to pursue alternative technological pathways, strengthen domestic manufacturing, and reduce dependence on Western suppliers. China is also investing in other semiconductor technologies and manufacturing approaches, which are discussed in the subsequent sections of this paper.

China's Strategic Technological Adaptation

U.S. restrictions have encouraged China to pursue multiple pathways toward technological resilience. Restrictions on EUV equipment complicate leading-edge fabrication, but do not prevent

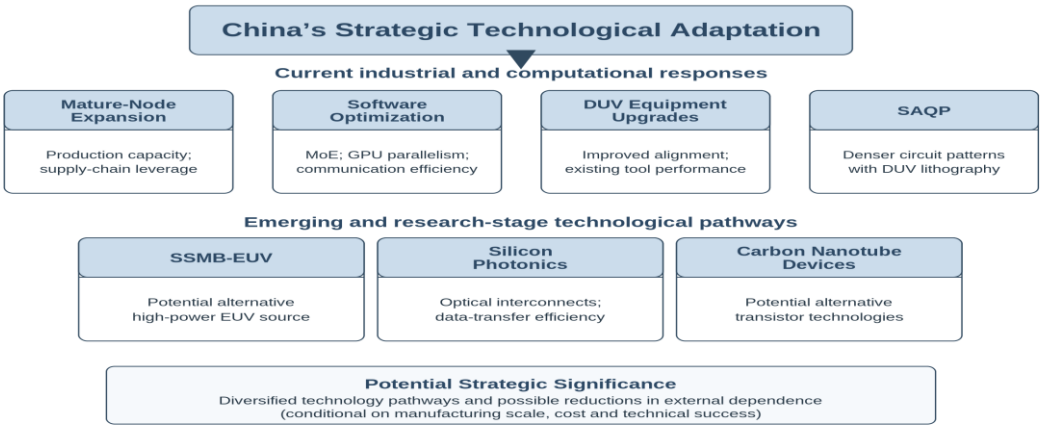
all advanced-node production through DUV multi-patterning, though the latter can carry substantial cost, yield, and complexity disadvantages. In May 2024, Beijing established the third phase of its National Integrated Circuit Industry Investment Fund, commonly known as the Big Fund III, with registered capital of approximately $47.5 billion (344 billion yuan), primarily aimed at strengthening indigenous semiconductor manufacturing, equipment production, and technological self-sufficiency (Priyadarshi, 2024; Reuters, 2024a).

China's determination is further reflected in its growing expenditure on semiconductor manufacturing equipment, which reached $49.6 billion in 2024, representing a 35% increase over the preceding year (SEMI, 2025). These massive financial commitments underscore Beijing's determination to overcome Western technological restrictions and establish a more autonomous semiconductor ecosystem.

The massive domestic investor confidence in China's semiconductor industry is further reflected in the recent initial public offerings (IPOs) of Chinese semiconductor companies Moore Threads and MetaX. The share prices of Moore Threads and MetaX surged by approximately 400% and 700%, respectively, on their stock market debuts in December 2025, reflecting growing investor enthusiasm for China's drive toward semiconductor self-sufficiency (Reuters, 2025a; Zhang, 2025). Additionally, China is achieving significant breakthroughs in software innovation, which are discussed in the subsequent section of this paper.

China is simultaneously expanding mature-node semiconductor manufacturing, which supplies components for automotive systems, consumer electronics, infrastructure, and defense-related products. This strategy can provide commercial scale and potential supply-chain leverage, even though mature-node capacity is not interchangeable with production of the most advanced AI accelerators. The following sections examine the implications and limitations of this adaptation.

Figure 2: China's Strategic Technological Adaptation



Note. Author's conceptualization. Pathways differ in technological maturity; strategic effects are potential rather than established.

Mature-Node Semiconductor Capacity and Supply-Chain Dependence

Legacy chips, also known as mature-node semiconductors, as highlighted in the U.S. CHIPS Act regulations of 2023, generally refer to semiconductors manufactured using process nodes of 28 nm or above. In comparison, advanced semiconductors are typically manufactured using process nodes of 14/16 nm or below (Goujon et al., 2024). Although there is no universally accepted definition of "cutting-edge" and "highly advanced" semiconductors, the former category generally includes chips manufactured using 5 nm or smaller process nodes, while the latter may encompass 7 nm and 10 nm technologies (Shivakumar, 2023). However, considering the continuing relevance of Moore's Law, these classifications are likely to evolve with technological advancements (Intel, 2023).

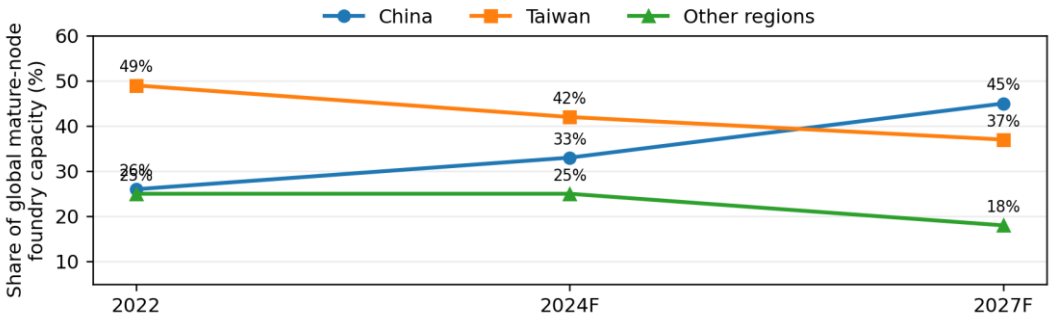
Legacy chips, despite their name, should not be considered technologically obsolete. In fact, the automotive, electronics, and mobile phone industries continue to rely heavily on mature-node semiconductors. These chips are expected to account for approximately three-fourths of global semiconductor demand for the foreseeable future, highlighting their continued importance in the global semiconductor ecosystem (Rühlig, 2024).

Before delving into China's strategy for manufacturing advanced semiconductor chips, it is pertinent to highlight the Chinese Communist Party's (CCP) efforts to establish dominance in the legacy-chip market. China is rapidly expanding its mature-node semiconductor manufacturing capacity by establishing new fabrication facilities. According to Gloden (2023), experts predict that the number of legacy-chip factories established in China could surpass the total number opened in the rest of the world. This expansion may give China considerable control over the global legacy-chip market and provide significant leverage over semiconductor buyers worldwide.

Former U.S. Deputy National Security Adviser Matt Pottinger has expressed similar concerns regarding China's potential monopoly over the legacy-chip market, given the importance of these semiconductors for commercial and military applications. Another semiconductor industry expert, Dan Hutcheson, has also highlighted that China possesses the capacity and infrastructure to mass-produce legacy chips, making it difficult for other manufacturers to compete because of the relatively low profit margins associated with this technology (Lee et al., 2022).TrendForce similarly projected that China's share of global mature-node foundry capacity could reach approximately 45% in 2027, compared with around one-third in its 2024 estimate(TrendForce, 2024).

Figure 3

Forcast Mature Node Foundry Capacity by Region, 2022-2027



Note. Reproduced from percentages attributed to TrendForce (2024);

In early 2022, the U.S. Department of Commerce released the results of a survey addressing the semiconductor shortage, revealing that firms faced their most acute shortages not in cutting-edge chips but in legacy chips manufactured using process nodes of 40 nm or larger (U.S. Department of Commerce, 2022). The U.S. automobile industry relies almost entirely on legacy chips, which account for approximately 95% of its total semiconductor consumption. The average number of chips per vehicle doubled between 2017 and 2021, reaching approximately 1,700, and this figure is expected to increase further as cars and trucks incorporate advanced safety features and automated driving capabilities (Shivakumar et al., 2023).

The shortage of mature chips also affected manufacturers of consumer electronic products. In 2021, Apple was forced to curtail its production plans for iPhones and other products because of shortages of legacy chips. In the case of the iPhone 13 Pro Max, shortages of peripheral components costing just a few cents, such as power management chips, transceivers, and connectivity devices, disrupted production. Importantly, such chips are not exclusive to iPhones, smartphones, or consumer electronics but are also widely used in computers, data centers, home appliances, and connected cars (Shivakumar et al., 2023).

A dispute over a small group of uninhabited islands between China and Japan in 2010 demonstrated how political tensions could disrupt critical technology supply chains. Following Japan's detention of a Chinese fishing boat captain near the disputed Senkaku Islands, China reportedly imposed informal restrictions on exports of rare-earth materials to Japan. These materials are crucial for electronics, semiconductor-related technologies, and other advanced industrial applications. This unexpected interruption caught Japanese industries off guard, disrupted supply chains, and compelled policymakers to reconsider the country's dependence on a single foreign supplier. Although China denied imposing an official embargo, the incident left a lasting impression on Japan

and served as a reminder that control over critical technological inputs could be used as leverage during political disputes (Kalantzakos, 2018).

China's expansion in mature-node chips therefore warrants serious attention from Washington and allied capitals. The strategic issue is not a presumed inevitable monopoly but the possibility that concentration in selected components could generate dependencies and political leverage during crises.

AI Software Optimization under Hardware Constraints

China is increasingly addressing the limitations imposed by U.S. semiconductor export controls through software optimization and more efficient utilization of available computing resources. While American AI developers have relatively greater access to advanced semiconductor technologies, Chinese companies face stronger incentives to extract maximum computational performance from available hardware. Consequently, techniques such as horizontal scaling, GPU parallelism, dynamic computation, mixture-of-experts (MoE) architectures, and communication optimization have become particularly important for China. Although these approaches are also employed by American companies, their strategic significance for China is greater because they provide alternative means of sustaining AI development despite restrictions on access to cutting-edge processors.

One important approach is **horizontal scaling**, a system-level computing concept that involves connecting a larger number of graphics processing units (GPUs) or servers to distribute computational workloads. Rather than depending exclusively on a few extremely powerful processors, developers can combine the capabilities of multiple available GPUs to perform complex AI computations. However, adding more processors does not automatically increase performance proportionately, as communication delays and inefficient workload distribution can reduce their effectiveness. To address these limitations, developers employ **GPU parallelism**, which allows processors to execute different portions of a computational task simultaneously. Three important techniques are data parallelism, tensor parallelism, and pipeline parallelism. Data parallelism divides training data among GPUs, tensor parallelism distributes large mathematical calculations across multiple processors, and pipeline parallelism assigns successive layers of an AI model to different GPUs. For instance, while one processor performs calculations on the initial layers of a model, another can process subsequent layers of an earlier batch. These techniques, combined with automatic load balancing, help minimize idle processing time and improve the utilization of available computing resources (Narayanan et al., 2021).

Additional efficiency gains are achieved through **dynamic or conditional computation**, which reduces the need to activate every parameter of an AI model for each calculation. One prominent implementation is the **mixture-of-experts (MoE) architecture**, which divides portions of a neural network into multiple expert subnetworks. Instead of activating every expert, a routing mechanism selects a limited number of experts to process a particular input. This reduces the computational requirements of individual operations while allowing models to retain a much larger overall

parameter capacity. However, the complete model still requires substantial memory and computing infrastructure to store and coordinate its parameters (Bengio et al., 2013; Shazeer et al., 2017).

Chinese AI developers have demonstrated the practical significance of these techniques. **DeepSeek-V3**, for example, incorporates approximately **671 billion parameters but activates only 37 billion for each token**, substantially reducing the computation required compared with activating the entire model. DeepSeek also employs optimized GPU communication and load balancing to improve training efficiency (DeepSeek-AI, 2024). Similarly, **Moonshot AI's Kimi K2.5** employs a mixture-of-experts architecture with approximately **one trillion total parameters, of which only 32 billion are activated per token** (Moonshot AI, 2026). These models demonstrate how Chinese developers are utilizing architectural innovations to develop increasingly capable AI systems while controlling computational requirements.

Further improvements in distributed AI training are achieved through efficient communication between GPUs. Two important techniques are **reduce-scatter and all-gather**. In reduce-scatter, multiple GPUs combine their calculated results and distribute the resulting data into separate portions, allowing each processor to retain only its assigned share. In all-gather, the GPUs exchange these portions so that every processor receives the complete combined information. For example, when several GPUs jointly process an AI model, reduce-scatter allows them to combine their results while retaining separate portions, whereas all-gather enables every GPU to obtain the complete result when required. These techniques help coordinate parallel computations and, when implemented efficiently, can reduce communication bottlenecks and improve the utilization of available computing resources (NVIDIA, n.d.).

Taken together, horizontal scaling, GPU parallelism, conditional computation, MoE architectures, automatic load balancing, and communication optimization provide China with alternative approaches to mitigating hardware constraints. These techniques cannot entirely compensate for limited access to advanced chips, particularly because large computing clusters still require substantial memory, reliable interconnects, and considerable energy. Nevertheless, their growing application demonstrates that technological competition is not determined solely by access to the most advanced semiconductor manufacturing nodes. While American companies employ similar techniques to improve performance, efficiency, and cost-effectiveness, **Chinese developers face the additional strategic imperative of sustaining technological progress under external restrictions**. These developments therefore illustrate how U.S. export controls can encourage Chinese innovation in computational efficiency, supporting Beijing's broader pursuit of technological self-sufficiency.

Upgrading Existing DUV Lithography Equipment

China is also upgrading its existing deep ultraviolet (DUV) lithography machines, particularly their lenses, alignment sensors and mechanical platforms used to position silicon wafers, to overcome restrictions on advanced semiconductor manufacturing equipment. According to Olcott (2025), Chinese semiconductor manufacturers have acquired upgraded components from secondary markets to improve the performance of older ASML Twinscan NXT:1980i machines.

These modifications improve the precision with which successive circuit patterns are aligned on silicon wafers, enabling manufacturers to increase the production of advanced semiconductors. Such improvements are particularly important because Chinese manufacturers increasingly rely on multiple-patterning techniques (discussed later in paper), which involve repeated lithographic exposures and processing steps, to manufacture 7 nm-class chips without access to extreme ultraviolet (EUV) lithography equipment. Although multiple patterning increases manufacturing complexity, production costs, and the risk of defective chips, improvements in equipment precision and efficiency can help mitigate these limitations (Olcott, 2025; Nie et al., 2025).

These developments demonstrate China's growing ability to extract greater performance from existing semiconductor manufacturing infrastructure rather than relying exclusively on access to newer equipment. While improvements in DUV machines cannot completely compensate for the advantages of EUV lithography, they provide Chinese manufacturers with an alternative pathway to advance domestic semiconductor production under Western export restrictions. This approach is further complemented by advanced multiple-patterning techniques, particularly self-aligned quadruple patterning (SAQP), which enable the fabrication of denser circuit patterns using existing DUV lithography technology.

Self-Aligned Quadruple Patterning (SAQP): A DUV Alternative

Self-aligned quadruple patterning (SAQP) is an advanced semiconductor manufacturing technique that allows manufacturers to create smaller and more closely spaced circuit patterns on silicon chips using existing lithography machines. Instead of attempting to produce extremely fine patterns in a single step, SAQP begins with a relatively simple pattern and using it as a reference, creates additional, closely spaced lines. Using this technique, the number of patterned lines can be increased approximately fourfold, allowing manufacturers to produce denser semiconductor circuits without relying exclusively on more advanced lithography equipment. SAQP can extend deep-ultraviolet (DUV) lithography to smaller features, but additional masks, pattern complexity, defects, and overlay constraints can raise costs and affect yields (imec, 2019; Siemens Digital Industries Software, 2025).

Huawei filed a patent for an advanced SAQP manufacturing method in September 2021, which was published in March 2024 and formally granted in October 2025. The patented technique improves flexibility in circuit-pattern design and could help Chinese manufacturers produce more advanced, potentially 5 nm-class, semiconductors using existing DUV equipment (Huawei Technologies Co., Ltd., 2025; Shilov, 2024).

Huawei also surprised Western observers with the launch of its Mate 60 Pro smartphone in 2023, powered by the domestically manufactured Kirin 9000S processor using SMIC's 7 nm-class technology (TechInsights, 2023). While the company has not revealed processor's manufacturing details, SMIC and Huawei's submission of SAQP patents early in 2021 reveal that Kirin 9000S processors might have been manufactured using the same technique. The complexity of multiple

patterning was previously demonstrated by Intel's difficulties in developing its initial 10 nm manufacturing process, which suffered production delays and low yields (Shilov, 2018).

In December 2025, TechInsights confirmed that Huawei's Kirin 9030 processor was manufactured using Semiconductor Manufacturing International Corporation's (SMIC) N+3 process, an improved version of its earlier 7 nm-class technology that also employs advanced DUV multiple-patterning techniques to achieve greater transistor density. Although this process represents a significant technological advancement, it remains less advanced than the commercial 5 nm processes employed by TSMC and Samsung (TechInsights, 2025). Commenting on China's progress, TechInsights Chief Strategy Officer Dan Kim acknowledged the significant technological achievements of Chinese semiconductor manufacturers despite their restricted access to the advanced equipment available to leading international competitors (Olcott, 2025).

These developments, together with Huawei's patented SAQP technology, demonstrate China's determination to overcome Western semiconductor restrictions through improvements in existing manufacturing processes and alternative technological approaches.

Steady-State Microbunching EUV Lithography (SSMB-EUV)

Another unconventional technological solution in which China is making significant progress is steady-state microbunching extreme ultraviolet (SSMB-EUV) lithography. This emerging technology could provide an alternative pathway for generating the high-power EUV light required for advanced semiconductor manufacturing. Before explaining SSMB-EUV, it is pertinent to understand the existing method of producing EUV light and the technological advantages that an alternative source could offer.

Modern EUV lithography systems employ light with a wavelength of 13.5 nanometres, enabling manufacturers to produce extremely fine circuit patterns required for advanced semiconductor chips. The existing commercial technology, developed by ASML, generates EUV light through a technique known as **laser-produced plasma (LPP)**. In this process, microscopic droplets of molten tin are injected into a vacuum chamber and struck by powerful laser pulses. The laser converts the tin into extremely hot plasma, which emits EUV radiation at a wavelength of 13.5 nm. This light is subsequently directed through a series of highly specialized multilayer mirrors, typically incorporating alternating layers of molybdenum and silicon, before reaching the silicon wafer. Conventional lenses cannot be used because EUV light is strongly absorbed by most materials (ASML, n.d.).

One major challenge associated with this technology has been increasing the power of the EUV light source to improve semiconductor manufacturing efficiency. Earlier research suggested that conventional tin-plasma sources were approaching practical limits of approximately 500 watts. However, technological advances have subsequently challenged this assumption. In April 2025, ASML successfully demonstrated a 1,000-watt EUV light source, achieved partly by increasing the frequency of tin droplets from 60,000 to 100,000 per second and improving laser-plasma

interactions. Although the 1,000-watt source had not yet entered commercial production, this development demonstrated that LPP technology could be extended beyond previously anticipated limitations (ASML, 2026). Nevertheless, SSMB-EUV remains a promising alternative because its accelerator-based mechanism offers a different pathway toward sustained kilowatt-level radiation, potentially with greater flexibility in light-source configuration and output.

Another challenge associated with conventional EUV lithography is the enormous size and complexity of the equipment. ASML's machines incorporate sophisticated optical systems, precision engineering, and extensive supporting infrastructure. China is therefore exploring an alternative approach that does not necessarily require the EUV light source to be housed within a conventional lithography machine. Researchers at Beijing's Tsinghua University have proposed using a large electron-storage-ring accelerator, potentially occupying an area comparable to a football field, to generate high-power EUV radiation. Earlier designs proposed an SSMB storage ring with a circumference of approximately 100–150 metres, while subsequent research explored alternative configurations ranging from 100–120 metres to approximately 200 metres, depending on the accelerator design and radiation requirements (Tang & Deng, 2022; Deng et al., 2026). Such a facility could potentially supply EUV radiation through multiple beamlines or radiators, creating opportunities to support several lithography applications from a centralized light source.

The underlying principle of SSMB-EUV is fundamentally different from conventional tin-droplet lithography. Instead of producing EUV light by striking tin droplets with lasers, SSMB employs a particle accelerator in which electrons circulate repeatedly around a storage ring. A precisely controlled laser interacts with the electrons, arranging them into extremely small groups known as microbunches. As these microbunches pass through an undulator, a series of magnets that causes the electrons to oscillate, they emit radiation in a coordinated manner. This synchronized emission, known as coherent radiation, enables a substantially greater output of light than would otherwise be produced by randomly distributed electrons(Deng et al., 2021).

China's progress in this technology has been supported by sustained scientific research and international collaboration. The SSMB concept was originally proposed by Alexander Chao and Daniel Ratner in 2010, while Tsinghua University established a dedicated research initiative in 2017 under the leadership of Professor Tang Chuanxiang. Chinese researchers subsequently collaborated with German scientists at Helmholtz-Zentrum Berlin and the Physikalisch-Technische Bundesanstalt to conduct experiments at the Metrology Light Source in Berlin. Their research culminated in a landmark study published in February 2021, demonstrating the fundamental mechanism of microbunching and coherent radiation in an electron storage ring (Deng et al., 2021).

Subsequent research has further strengthened the scientific foundations of this technology. In November 2023, researchers from Tsinghua University published a study proposing an improved accelerator design capable, according to theoretical calculations, of generating kilowatt-level EUV radiation at 13.5 nm (Li et al., 2023). In September 2025, Tsinghua researchers presented a more comprehensive high-power SSMB-EUV source design and reported encouraging experimental observations of coherent radiation across repeated electron revolutions (Pan et al., 2025). Further

progress was reported at the International Particle Accelerator Conference in 2026, where Chinese and German researchers presented experimental evidence of coherent radiation following multiple rounds of laser modulation, representing another step toward sustained microbunching (Kruschinski et al., 2026). Additionally, research published in October 2026 investigated methods of controlling electron-beam instabilities, addressing an important technical challenge for maintaining reliable accelerator operation (Dai et al., 2026).

SSMB-EUV offers several potential advantages over conventional laser-produced-plasma lithography. First, its accelerator-based design could generate kilowatt-level or potentially higher EUV power, supporting more efficient and faster semiconductor manufacturing. Second, the possibility of incorporating multiple radiation sources within a single storage ring could improve the utilization of a centralized facility. Third, SSMB could provide highly coherent radiation with a controlled wavelength and relatively stable output, which are desirable characteristics for precise semiconductor patterning. Furthermore, because the process does not depend on vaporizing tin droplets, it could avoid the tin-debris management challenges associated with conventional plasma-based EUV sources. These characteristics make SSMB an attractive candidate for future semiconductor lithography, although their practical advantages will depend on successful engineering development and integration into manufacturing systems (Tang & Deng, 2022; Deng et al., 2026).

Although SSMB-EUV remains at the research and development stage, the experimental achievements and continuing technological improvements demonstrate China's sustained efforts to develop alternatives to Western-controlled semiconductor manufacturing equipment. If successfully commercialized, SSMB-EUV could significantly reduce one of the major technological barriers confronting China's advanced semiconductor industry, particularly its dependence on foreign EUV light-source technology.

Such a development could alter the future balance of semiconductor manufacturing capabilities and weaken the long-term effectiveness of export restrictions. From a defensive realist perspective, China's pursuit of SSMB-EUV illustrates how external technological constraints can stimulate indigenous innovation, potentially enabling a constrained state to reduce its strategic vulnerability and strengthen its technological autonomy.

Emerging Semiconductor Technologies: Silicon Photonics and Carbon Nanotube-Based Semiconductors

Another important area China is focusing on is **silicon photonics**, an emerging technology that integrates optical and electronic components using existing semiconductor manufacturing techniques. Unlike conventional electronic systems, which rely on electrons to transmit information, silicon photonics uses photons (light) for high-speed data transmission within and between chips. This technology can overcome some of the limitations associated with electrical signals, including resistance, heat generation and restricted communication bandwidth, allowing faster transmission of larger volumes of data with potentially lower energy consumption. Although leading semiconductor

manufacturers, including Intel, are exploring this technology, China has also made significant progress. In September 2024, Jiufengshan Laboratory (JFS) in Hubei successfully integrated an indium phosphide laser light source onto a silicon-based chip using an eight-inch silicon-on-insulator wafer. This achievement, reported as the first of its kind in China, could help overcome important communication bottlenecks in advanced processors and data centres, particularly those supporting AI applications (Intel, 2024; Shen, 2024).

China has been pursuing technological leadership in photonics since the early 2000s. According to Tematys, a France-based photonics market analysis firm, China's share of the global photonics market increased from **10% in 2005 to 32% in 2022**. In contrast, Europe's and North America's market shares remained around 15% each during the same period (Pool, 2024). Although these figures represent the broader photonics industry rather than silicon photonics alone, they demonstrate China's rapidly expanding industrial capabilities in optical technologies. Coupled with advances in semiconductor manufacturing, China's progress in silicon photonics represents another unconventional technological approach that could strengthen its competitiveness against Western semiconductor manufacturers by improving data transmission and reducing dependence on conventional electrical interconnections.

Alongside silicon photonics, **carbon nanotube (CNT)-based semiconductors** represent another promising technological pathway being explored by Chinese researchers. In January 2025, scientists from Peking University and Beijing University of Posts and Telecommunications published research demonstrating advanced carbon nanotube-based circuits capable of operating in three distinct logic states. The achievement, described in contemporary reporting as a breakthrough in carbon-based AI chips, offers a potential alternative to conventional silicon-based computing (Zhang, 2025; Zhu et al., 2025). Unlike traditional binary computing, which operates using two states (0 and 1), this technology employs **ternary logic**, incorporating a third computational state. By allowing electronic circuits to represent information through three states instead of two, ternary computing could potentially increase information density, reduce circuit complexity, and improve energy efficiency.

The underlying innovation involves carbon nanotube transistors, which use extremely small cylindrical structures made from carbon atoms. These nanotubes possess favorable electrical properties, including high data transfer rate and the potential for lower power consumption compared with conventional silicon-based transistors (Zhu et al., 2025). These characteristics make carbon nanotubes promising candidates for the development of smaller, faster, and more energy-efficient computing systems.

Carbon nanotube technology offers a potential pathway beyond the scaling limitations of conventional silicon transistors. Their extremely small dimensions and favorable electrical properties could enable the development of smaller, faster, and more energy-efficient transistors while reducing current leakage and power consumption. If successfully commercialized, CNT-based semiconductors could support further improvements in transistor density and computing performance as conventional silicon miniaturization approaches its physical and economic limits

(Zhang et al., 2025). Its electrical characteristics and potential scalability could support future developments in AI, machine learning, high-performance computing, and energy-efficient electronic systems.

However, despite these advantages, CNT-based semiconductor circuits have not yet achieved the integration density and industrial manufacturing maturity of advanced commercial silicon chips. According to **Peng Lianmao, a member of the Chinese Academy of Sciences**, carbon nanotube-based chips could become mainstream within the next 10–15 years, provided that the technological and manufacturing challenges are successfully addressed (Zhang, 2025).

If successfully commercialized, silicon photonics and carbon nanotube-based semiconductors could reshape future computing architectures by improving information transmission, processing efficiency, and energy consumption. These developments could also provide China with additional technological pathways beyond conventional silicon-chip miniaturization, potentially reducing its dependence on semiconductor technologies and manufacturing capabilities currently dominated by Western companies and their allies. Together with China's progress in lithography, software optimization and indigenous semiconductor manufacturing, these emerging technologies demonstrate Beijing's determination to pursue alternative approaches that could strengthen its technological self-sufficiency and influence the future balance of technological power in the U.S.–China semiconductor rivalry.

Policy Implications for the United States

The unintended consequences of U.S. semiconductor restrictions, including financial strain on American firms, accelerated Chinese efforts toward technological self-sufficiency and the fragmentation of global supply chains, underscore the broader implications of technology containment policies. Considering these factors, the long-term effectiveness of restrictive measures remains uncertain, raising questions about whether the United States should reassess its semiconductor strategy to balance national security concerns with economic and industrial competitiveness. This calls for a recalibration of U.S. policies to safeguard its strategic interests while avoiding measures that might inadvertently accelerate China's pursuit of semiconductor self-sufficiency.

Second, the United States, in collaboration with its allies, particularly the Netherlands, Taiwan, South Korea and Japan, must expand its technological focus to include areas in which China is actively investing, such as silicon photonics, self-aligned quadruple patterning (SAQP), steady-state microbunching EUV (SSMB-EUV) lithography and carbon nanotube-based semiconductors. Although some of these technologies remain at different stages of development, their successful commercialization could reshape future semiconductor manufacturing capabilities. Consequently, Washington should prioritize research and development in these emerging technologies rather than concentrating exclusively on maintaining its advantage in existing semiconductor manufacturing processes.

Third, the United States should accelerate efforts to establish a more comprehensive and self-reliant semiconductor manufacturing ecosystem on its own soil. This should include continued investment in advanced fabrication facilities, cutting-edge interconnects, data centres and advanced packaging technologies that enhance system performance and complement improvements in software and algorithmic efficiency. Such measures are particularly important given the growing tensions across the Taiwan Strait and the potential consequences of a disruption to Taiwan's semiconductor industry.

The strategic significance of this dependence is reflected in estimates concerning Taiwan's dominance in advanced semiconductor manufacturing. A Semiconductor Industry Association and Boston Consulting Group study estimated that Taiwan accounted for approximately 92% of global manufacturing capacity for the most advanced semiconductors below 10 nm at the time of its assessment (Semiconductor Industry Association [SIA] & Boston Consulting Group [BCG], 2021). In May 2024, U.S. Commerce Secretary Gina Raimondo acknowledged that approximately 92% of America's leading-edge chips were purchased from Taiwan's TSMC, highlighting the potential consequences of geopolitical instability in the Taiwan Strait (Shepardson, 2024).

The $52.7 billion investment authorized under the CHIPS and Science Act of 2022 represents an important step toward reducing this dependence, although sustained financial investment, government oversight and industrial coordination remain essential to compete with China's extensive state-backed semiconductor initiatives (Sutter et al., 2023). The commencement of mass production of advanced 4 nm-class semiconductors at TSMC's fabrication facility in Phoenix, Arizona, in the fourth quarter of 2024 represents another positive development in strengthening domestic U.S. semiconductor manufacturing capabilities (Bourzac, 2024; TSMC, n.d.).

These efforts have been reinforced by substantial additional investments. In July 2026, TSMC announced a further $100 billion investment in Arizona, bringing its total planned U.S. investment to **$265 billion**, including advanced semiconductor fabrication and packaging facilities (U.S. Department of Commerce, 2026). Similarly, Micron Technology increased its planned domestic manufacturing and research investments to **more than $250 billion through 2035**, while GlobalFoundries announced **$16 billion** in investments to expand semiconductor manufacturing and advanced packaging capabilities in New York and Vermont (Micron Technology, 2026; GlobalFoundries, 2025). These massive financial commitments demonstrate Washington's growing determination to strengthen its domestic semiconductor ecosystem and reduce strategic dependence on foreign supply chains. Nevertheless, sustained government support, industrial coordination, and technological innovation remain essential to ensure that these investments translate into long-term manufacturing competitiveness.

Fourth, a reassessment of U.S. semiconductor export-control policies is essential to strike an appropriate balance between safeguarding national security and protecting economic interests. Rather than imposing sweeping restrictions, Washington should adopt a more selective approach that continues to restrict China's access to the most sensitive military-relevant semiconductor technologies while permitting carefully regulated commercial exports where security risks can be adequately managed. Such a strategy could help American semiconductor companies retain their

market share in China, preserve revenue for future research and development, and discourage Chinese firms from shifting entirely toward indigenous alternatives.

The January 2026 decision to permit case-by-case export licensing for Nvidia's H200 and comparable processors, subject to security conditions, illustrates an approach that attempts to balance commercial interests with national security requirements (Bureau of Industry and Security, 2026). Regular assessments of the economic consequences and strategic effectiveness of export controls would further help Washington avoid policies that inadvertently accelerate China's technological self-sufficiency and the emergence of a parallel semiconductor ecosystem.

The proposed SAFE Chips Act of 2025 represents a further legislative initiative intended to tighten restrictions on advanced AI chip exports to foreign adversaries (Bureau of Industry and Security [BIS], 2024; U.S. Congress, 2025). However, excessively broad restrictions may unintentionally harm American semiconductor companies while encouraging Chinese firms to accelerate indigenous technological development. By refining these policies to target specific technologies, entities, and military applications, Washington could minimize unintended economic consequences while preserving its technological and strategic advantages.

Greater coordination with allies is equally important to prevent fragmentation of the global semiconductor industry in ways that could undermine U.S. interests. Export-control policies are more effective when supported by key partners that control critical components of the semiconductor supply chain, including lithography equipment, advanced memory, semiconductor materials, and manufacturing facilities. At the same time, Washington should avoid unnecessarily accelerating technological bifurcation, as the emergence of a parallel Chinese semiconductor ecosystem could gradually reduce American leverage and diminish its influence over international technological standards and governance mechanisms. Consequently, closer cooperation with allied countries should be accompanied by a carefully calibrated approach that preserves strategic advantages without encouraging complete technological decoupling.

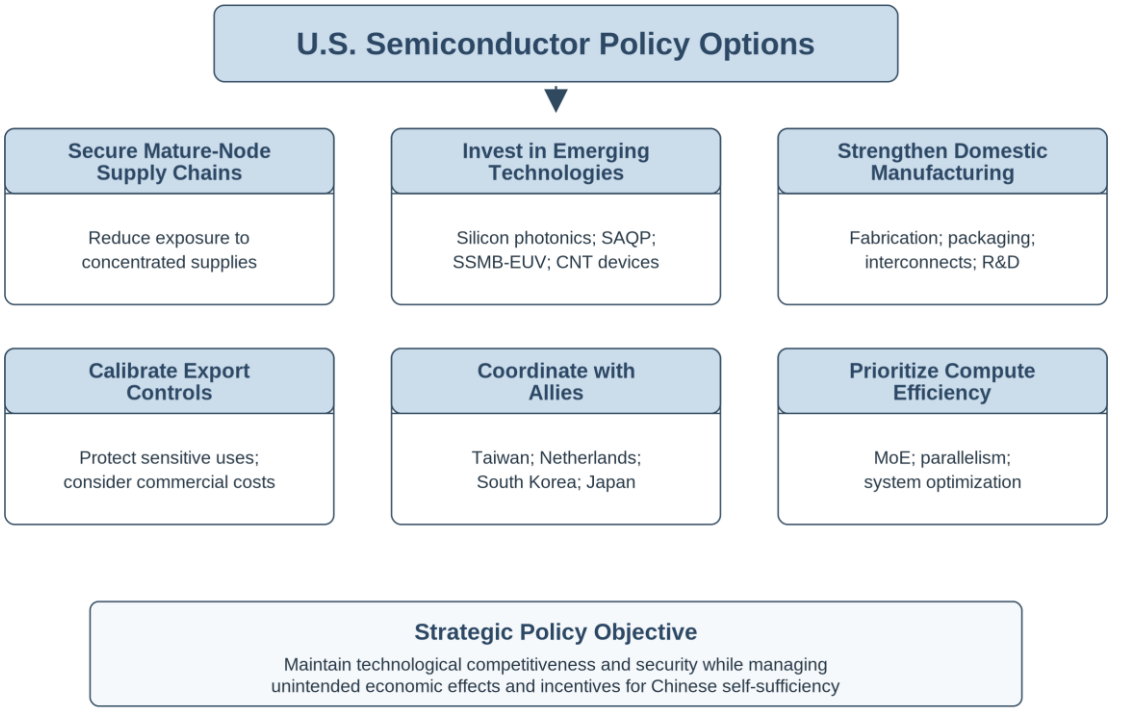
Lastly, U.S. semiconductor strategy should place equal emphasis on AI computational efficiency and software optimization. Although American developers currently enjoy relatively greater access to advanced semiconductor hardware, this advantage could narrow as Chinese companies increasingly employ techniques such as horizontal scaling, GPU parallelism, dynamic computation, mixture-of-experts architectures, and communication optimization.

The progress demonstrated by Chinese AI developers, including DeepSeek and Moonshot AI, illustrates the growing strategic importance of improving computational efficiency alongside hardware capabilities. Greater investment in communication-efficient training, advanced model architectures, dynamic computation and system-level optimization would help ensure that American technological leadership remains resilient even as competing countries develop alternative means of overcoming hardware restrictions.

Taken together, these policy considerations suggest that the United States must adopt a more comprehensive semiconductor strategy that combines targeted export controls, domestic manufacturing capacity, allied coordination, investment in emerging semiconductor technologies, and computational efficiency. Such an approach could help preserve American technological leadership while limiting the unintended incentives for Chinese technological self-sufficiency created by restrictive policies.

Figure 4

Policy Considerations for the United States in the Semiconductor Race



Note. Author's conceptualization based on the policy recommendations discussed in the manuscript.

Conclusion

The U.S.–China semiconductor competition is reshaping global technological and geopolitical dynamics, especially for AI and defense-related computing. China's responses include mature-node capacity expansion, software optimization, DUV multi-patterning and research into silicon photonics, carbon-nanotube devices, and alternative EUV sources. These developments are at different levels of technological readiness. Their long-term effects are uncertain, even as export controls seek to limit access to advanced hardware and production tools.

Defensive realism helps explain why the United States seeks to protect security advantages and why China seeks greater technological autonomy in response. Technological determinism draws attention to the changing possibilities created by advances in computing and fabrication, although technology does not determine political outcomes independently of institutions and policy choices.

Beyond strategic considerations, the economic repercussions for U.S. firms and allied economies cannot be overlooked, as reduced market access and declining revenues could weaken the very industries the U.S. seeks to protect. To navigate this evolving landscape, the U.S. must strengthen collaboration with its allies, invest in emerging semiconductor technologies, and recalibrate export controls to prevent policies that may inadvertently accelerate China's self-sufficiency.

Ultimately, the semiconductor war is not merely a competition over chips but a defining element of U.S.–China strategic rivalry, shaping the future of global power structures and technological supremacy in the years to come.

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