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Research on the innovation path of China's semiconductor industry in the post-Moore era

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Abstract:

In the post-Moore era, the global semiconductor industry faces problems such as the slowdown of Moore's Law, rising costs of advanced processes, and challenges in material and architecture innovation. China's semiconductor industry has gaps in technological innovation, supply chain security, and market competition, but the technological changes in the post-Moore era provide it with opportunities for innovative breakthroughs. This study systematically analyzes the development status, international competition landscape, technological challenges, and innovation paths of China's semiconductor industry. The study points out that China should increase R&D investment in advanced packaging, heterogeneous integration, new material applications, and new semiconductor architectures, and promote industry-university-research cooperation to build an independent and controllable industrial ecosystem. In the short term, China can focus on breakthroughs in GAA transistors and chiplet technology; in the medium term, focus on FD-SOI process and planar process optimization; in the long term, it needs to deploy three-dimensional integrated circuit technology and establish an all-round innovation system. The study provides theoretical support and practical paths for the innovative development of China's semiconductor industry in the post-Moore era.

Keywords: post-Moore era, semiconductor, industrial ecology, innovation path

1. Introduction

As the cornerstone of modern information technology, the semiconductor industry plays a vital role in global economic and technological competition [1] . Since the mid-20th century, the development of semiconductor technology has followed Moore's Law, which states that the number of transistors on an integrated circuit doubles approximately every two years. This law has played a vital role in promoting computing power, reducing power consumption, and shrinking chip size [2] . However, as process technology continues to approach physical limits, the miniaturization of silicon-based CMOS technology faces severe challenges, making it increasingly difficult to continue Moore's Law, and the global semiconductor industry is gradually entering the post-Moore era [3] .

In terms of More Moore technology, researchers continue to explore new processes and new structures to further shrink chip feature sizes and improve device performance. From traditional planar transistors to FinFETs (fin field-effect transistors), and then to the GAA (gate-all-around transistors) that have attracted much attention in recent years, innovations in transistor structures have significantly improved electrical performance and reduced device power consumption [4] . At the same time, extreme ultraviolet (EUV) lithography technology has broken through the resolution limitations of traditional lithography, allowing chip feature sizes to be further reduced [5] . Compared with Deep Moore's Law, More than Moore's Law has opened up a new path for the sustainable development of the semiconductor industry and can play a key role in areas such as data centers, high-speed interconnection and 5G communications. [6] [7] .

In the global semiconductor competition landscape, China's semiconductor industry has achieved remarkable development in the past few decades, but there is still a large gap between it and developed countries in terms of technological innovation, industrial scale and international competitiveness [8] . The industrial transformation in the post-Moore era has provided China with unprecedented opportunities as well as brought many challenges. In-depth research on innovation paths is of great significance for breaking through technological bottlenecks, achieving leapfrog development, and enhancing international competitiveness [9] . China can accelerate its layout in emerging technology fields and promote the development of key areas such as advanced packaging, heterogeneous integration, and silicon photonics to reduce its dependence on overseas technology and enhance the independent and controllable capabilities of the semiconductor supply chain [10] .

This study aims to analyze the innovation path of China's semiconductor industry in the post-Moore era, sort out the current status of industrial development, analyze challenges and opportunities through the study of relevant theories and practices, and provide theoretical and practical guidance for industrial innovation and development. Specifically, the direction of innovation is clarified by studying the development trend of semiconductor technology, analyzing the current status of China's semiconductor industry to find out the problems and gaps, and studying successful cases at home and abroad to summarize the experience and lessons, so as to provide reference for industrial innovation.

2. Current status of semiconductor industry development in the post-Moore era

2.1 International Development Trends

The global semiconductor industry has entered the post-Moore era. Leading companies such as TSMC, Samsung, and Intel, relying on their technological accumulation and capital investment, continue to innovate in advanced processes and packaging, and dominate industry development. TSMC has been advancing more advanced processes based on 5nm mass production, and has launched advanced packaging technologies such as InFO WLP, CoWoS, and InFO SoW, which have significantly improved chip performance and integration [11] . Samsung was the first to apply GAA transistors in the 3nm process, promoted 2nm research and development, and jointly developed hybrid bonding and 3D packaging Foveros technology [12] . Intel has planned a process goal of five nodes in four years and has made breakthroughs in GAA, heterogeneous packaging and new materials. Its EMIB and Foveros packaging each have advantages in cost and performance, and it has developed ODI to enhance heat dissipation and power transmission capabilities [13] . In terms of the market, the scale of the global semiconductor industry continues to expand, and technological innovation has become the core driving force. WSTS predicts that the market will reach US$635.1 billion in 2024 and increase to US$718.9 billion in 2025 [14] . Despite a decline in 2023, SEMI predicts that it will rebound by nearly 20% in 2024 and is expected to exceed US$1 trillion in 2030 [15] . As a key supporting technology, advanced packaging has broad market prospects due to its advantages in power consumption control, heat dissipation and high-speed interconnection. BESI predicts that the demand for hybrid bonding equipment will reach 1,400 units by 2030, with a market size exceeding RMB 20 billion, with AI computing power demand becoming the main driving force [16] .

2.2 Current status of China's industry

2.2.1 Industry scale and structure

Driven by policy support, market demand and technological innovation, China's semiconductor industry is developing rapidly, with a market size of US$179.5 billion in 2023 and an estimated US$238 billion in 2027. However, investment declined in the first half of 2024, with total investment of approximately RMB 517.3 billion, a year-on-year decrease of 37.5%. Among them, investment in wafer manufacturing accounted for the largest proportion,

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reaching RMB 246.8 billion. IC design, materials, packaging and testing all declined to varying degrees. Only investment in semiconductor equipment grew against the trend, increasing by 45.9% year-on-year [17] . China's semiconductor industry chain covers IC design, wafer manufacturing, packaging and testing. IC design has developed rapidly, with the number of companies and technological levels continuing to improve, but it still lags behind international leading companies in high-end chip design and core technology [18] . In the wafer manufacturing stage, SMIC has achieved mass production of 14nm process technology and promoted the research and development of 7nm technology, but compared with TSMC and Samsung, there is still a large gap in process technology, production capacity and other aspects [19] . In the global foundry market, TSMC and Samsung dominate the market. The production capacity of domestic enterprises is difficult to meet market demand, and high-end chips still rely on imports [20] . The packaging and testing link is relatively mature and has a certain share in the global market. Investment growth will continue in January-June 2024. Domestic packaging and testing companies such as Changdian Technology have made great progress in scale and technology and are able to provide a variety of advanced packaging services [21] . However, in terms of advanced packaging technologies such as 3D packaging and chiplets, Chinese companies still lag behind the international leading level [22] .

2.2.2 Technical Level and Gap

In terms of process technology, Chinese semiconductor companies are working hard to catch up. As a leader, SMIC has continued to invest in research and development, and has successfully mass-produced 14nm process technology, providing advanced manufacturing services to domestic chip design companies to meet the needs of some high-performance chips. It is also actively promoting the research and development of 7nm process technology. But compared with TSMC and Samsung, the gap is significant. TSMC has achieved large-scale mass production of 5nm and is moving towards 3nm and more advanced processes. The 5nm process uses EUV technology to achieve high transistor density and low power consumption, leading the field of high-performance chip manufacturing. Samsung has mass-produced 3nm process technology, using GAA transistor technology, which can better control leakage and improve chip performance compared to FinFET. The leading position of international giants allows them to dominate the high-end chip market, and Chinese companies face greater technological challenges.

3. Challenges facing the semiconductor industry in the post-Moore era

3.1 Technical bottleneck

In the development of the semiconductor industry, Moore's Law has promoted technological progress, but as the process moves towards smaller nodes, it faces challenges in its continuation. The most advanced process is currently 3 nanometers, and TSMC and others are evolving towards 2 nanometers and smaller. In this process, process miniaturization encounters physical limits and cost problems. When the process reaches 10 nanometers and below, quantum effects become prominent. For example, quantum tunneling causes electrons to penetrate potential barriers and cause leakage, affecting chip stability and performance. At the same time, parasitic capacitance and resistance effects increase signal transmission delays [23] . In terms of cost, the R&D and production costs of advanced processes have risen sharply. Equipment such as EUV lithography machines are expensive, and R&D requires a lot of money and manpower. Low yields further increase costs. Chip designers also face rising costs and market risks.

3.2 Market Competition

The international semiconductor market is highly competitive, and companies from various countries have taken their place in the industry chain with their different advantages. The United States is known for its technological innovation, with Intel, Nvidia, and Qualcomm leading in the fields of microprocessors, GPUs, and communication chips. South Korea has performed well in memory chips, with Samsung and SK Hynix having strong manufacturing capabilities. Taiwan's TSMC is a global leader in advanced processes and foundry services, while Japan is strong in semiconductor materials and equipment, with companies such as Shin-Etsu Chemical, SUMCO, and Tokyo Electron mastering core technologies [24] . In contrast, Chinese companies are still constrained by factors such as technology, R&D, and ecosystems in the high-end chip market, and the advantages of international giants in technology, equipment, and markets pose strong pressure. Coupled with technological blockades and trade sanctions, Chinese companies face huge challenges and urgently need to accelerate independent innovation and localization of the industry chain.

3.3 Supply Chain and Geopolitical Risks

China's semiconductor industry is highly dependent on foreign countries for key materials and equipment, which poses a security risk to the supply chain. High-end silicon wafers and photoresists mainly rely on Japanese companies, and advanced lithography machines are monopolized by ASML of the Netherlands, making it difficult for Chinese companies to obtain key equipment and materials. Domestic equipment still lags behind foreign equipment in technology and performance, and the localization rate of key equipment is low, which restricts technological breakthroughs and industrial upgrading [25] . At the same time, geopolitical risks have intensified. The United States has imposed technology and equipment bans on Chinese companies, restructured the global industrial chain, restricted international cooperation and talent flow, and further compressed the development space of China's semiconductors. In the face of these challenges, China needs to accelerate the research and development of key technologies and enhance its independent and controllable supply chain capabilities.

4. Innovation Direction of Semiconductor Industry in the Post-Moore Era

4.1 Technological innovation

In the post-Moore era, advanced packaging has become the key to continuing Moore's Law and improving chip performance. Chiplet technology improves flexibility and yield through modular design, while 2.5D/3D packaging uses silicon interposers and vertical stacking to achieve efficient interconnection and is widely used in high-performance chips. New materials such as carbon nanotubes and graphene have excellent electrical properties, and compound semiconductors (such as silicon carbide and gallium nitride) have obvious advantages in power devices and high-frequency applications. At the same time, new architectures such as the open source RISC-V lower the design threshold and are suitable for the Internet of Things and edge computing; in-memory computing significantly optimizes the efficiency of AI and big data processing by integrating computing and storage.

4.2 Model Innovation

The design-technology collaborative optimization (DTCO) model promotes the integration of design and manufacturing, improves R&D efficiency, and reduces trial and error costs. It is particularly suitable for complex processes under advanced processes. At 7 nanometers and below, the design and manufacturing teams need to work closely together to balance performance and power consumption. It is also particularly important to build a complete industrial ecosystem. Chip design, manufacturing, packaging and testing, materials and equipment companies need to develop in a coordinated manner to meet the full-chain needs of high-demand products such as 5G chips. China has made progress in ecological construction, but it still needs to strengthen key technologies and collaborative innovation to achieve independent control and global competitiveness.

5. Research on the innovation path of China's semiconductor industry

Nano-Gate-All-Around (GAA) transistors and chiplet technology are the key directions for the development of China's semiconductors in the post-Moore era. Although progress has been made under the promotion of institutions such as the Chinese Academy of Sciences, they are still in the stage of technical verification, and the construction of the industrial ecosystem lags behind. Chiplet technology has been actively deployed by companies such as Changdian Technology and Tongfu Microelectronics due to its cost and performance advantages. Although initial results have been achieved, there is still room for improvement in standard setting and ecological integration. In the medium term, FD-SOI technology has broad prospects in IoT and 5G applications due to its low power consumption and high performance, but it is limited by manufacturing complexity and cost. At the same time, the development of new planar process paths can break through the bottleneck of miniaturization, reduce external dependence, and enhance independent control capabilities. In the long run, vertical devices and three-dimensional circuits will drive a significant leap in chip performance. Although technologies such as VGAA and 3D NAND have taken shape, they still face challenges in process, design tools, and heat dissipation. To achieve continuous breakthroughs, China urgently needs to build an innovation system covering basic research, applied innovation and transformation of results, promote collaboration among government, industry, academia and research, strengthen platform and talent construction, and improve intellectual property protection mechanisms to ensure technological independence and sustainable development.

6. Conclusion and Outlook

6.1 Research Summary

This study analyzes the innovation path of China's semiconductor industry in the post-Moore era. Against the backdrop of accelerated global technological evolution and supply chain reconstruction, China's semiconductor industry has achieved scale and technological progress driven by policies and markets, but there is still a gap with the international advanced level, especially in the fields of

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high-end chips, key equipment and materials. At the same time, intensified international competition, frequent trade frictions, and rising geopolitical risks have made China face multiple challenges in technology, market and supply chain. In response to these problems, the study proposes a development strategy with technological innovation and model innovation as the core, including the promotion of GAA transistor and chiplet packaging technology in the near term, the development of FD-SOI and new planar process paths in the medium term, and the realization of vertical three-dimensional integration and the construction of an all-round innovation system in the long term to enhance independent controllability and industrial competitiveness.

6.2 Future Prospects

Looking ahead, emerging applications such as artificial intelligence, 5G, and the Internet of Things will bring broad market opportunities to China's semiconductor industry. Faced with the continued growth in chip performance and energy efficiency, China must persist in technological innovation, deepen research and development in advanced packaging, new materials, and new architectures, and promote the implementation of emerging architectures such as RISC-V and in-memory computing. At the same time, it is necessary to strengthen design and manufacturing collaboration, promote the DTCO model, and build a complete industrial ecosystem to promote upstream and downstream collaboration and the integration of industry, academia, and research to improve the efficiency of results transformation. The government should continue to increase its support, optimize the innovation environment, and work closely with enterprises, universities, and research institutions to accelerate independent technological breakthroughs and industrial chain integration. In the post-Moore era, where multiple challenges and transformation opportunities coexist, China is expected to achieve leapfrog development of the semiconductor industry through continuous innovation and model optimization, enhance global competitiveness, and help the country's scientific and technological independence and high-quality development.

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