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Applications and Developments in Semiconductor Memory Technology

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Abstract: With the rapid evolution of information technology, semiconductor memory has become a cornerstone of modern computing, supporting big data, artificial intelligence, and the Internet of Things. Traditional magnetic storage technologies are increasingly unable to meet demands for speed, capacity, and energy efficiency, highlighting the urgency of advancing semiconductor memory research. Despite progress in DRAM, SRAM, and flash memory, existing studies reveal gaps in addressing production sustainability, high costs, and environmental challenges. This paper systematically reviews the development and industrial landscape of semiconductor memory, analyzes its manufacturing processes and associated pollutants, and evaluates emerging sustainable solutions such as advanced abatement systems and wastewater treatment strategies. It further explores cutting-edge alternatives, particularly Resistive Random Access Memory (ReRAM), which integrates high-speed and non-volatile features but still suffers from device variability, circuit complexity, and limited market readiness. Results show that innovative process optimization and architecture-aware training can partially mitigate these constraints, while sustainable practices significantly reduce environmental impacts. The study underscores that advancing semiconductor memory requires not only technological breakthroughs but also robust sustainability and intellectual property strategies, offering critical implications for global competitiveness, industrial upgrading, and the transition toward low-carbon intelligent infrastructures.

Keywords: semiconductor memory; DRAM/SRAM; flash storage; sustainable manufacturing; ReRAM

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1. Introduction

With the rapid advancement of information technology, human society generates massive volumes of data on a daily basis, driving storage demands to grow at an unprecedented pace. From early magnetic tapes and disks to contemporary semiconductor memories, data storage media have undergone continuous evolution [1]. Traditional magnetic recording technologies, constrained by complex mechanical structures, limited read-write speeds, and insufficient lifespan, have increasingly revealed their inability to meet the requirements of the big data era and high-performance computing [2]. Particularly under the impetus of mobile internet and artificial intelligence, the rising demands for faster data processing and higher energy efficiency have further accelerated the transformation of storage technologies.

Semiconductor memory, built upon solid-state electronic devices, offers advantages such as high speed, reliability, and miniaturization. Solid-state drives (SSDs) have progressively replaced mechanical hard drives in personal computers and mobile terminals, emerging as the mainstream storage option [3]. The high degree of integration in flash memory chips enables ultra-large capacity within compact dimensions, which is especially critical for space-constrained devices such as smartphones and tablets. In recent years, SSDs, together with DRAM and SRAM, have constituted the core infrastructure of modern information systems, supporting the development of cloud computing, the Internet of Things, and artificial intelligence applications [4].

Nevertheless, the advancement of semiconductor memory still faces significant challenges. First, its production cost remains higher than that of traditional magnetic recording media, hindering widespread adoption. Second, the manufacturing process entails substantial chemical usage and energy consumption, raising concerns about environmental pollution and sustainable development [5]. Despite these issues, ongoing exploration of novel materials, advanced fabrication techniques, and sustainable manufacturing methods suggests that semiconductor memory technology holds promise for further expanding its application boundaries while progressively addressing cost and environmental concerns.

Therefore, a systematic study of the applications and development of semiconductor memory is not only essential for understanding its strategic role in the big data era but also provides critical insights for industrial transformation, technological upgrading, and sustainable innovation.

2. Background and Current Status of Semiconductor Memory

2.1. Introduction to Semiconductor Memory

Semiconductor memory is a solid-state device manufactured using semiconductor integrated circuit technology, consisting of a large number of memory cells and input/output circuits [6]. Each memory cell stores information through binary states "0" and "1," making it an essential component of computers. It possesses advantages such as high access speed, large capacity, and compact size, while also being compatible with peripheral logic circuits, thereby enabling integration on a single chip and simplifying interface design. Based on functionality, semiconductor memory can be classified into three major categories: random-access memory (RAM), read-only memory (ROM), and serial memory. The most common forms encountered in daily life are main memory and flash memory [7].

2.2. Emergence and Development of Semiconductor Memory

Prior to the 1950s, computer memory primarily relied on magnetic drums, mercury delay lines, and Williams tubes, all of which were bulky and slow. In the 1950s and 1960s, core memory composed of ferromagnetic rings emerged, but it still failed to meet the high-speed demands of CPUs [8]. In 1970, Fairchild Semiconductor introduced the first large-capacity semiconductor memory, ushering in a new stage of storage technology. Since then, products have evolved from the earliest fast page mode (FPM) memory to DDR and RDRAM, with chip capacity expanding from 1 KB to 1 GB.

Today, the main forms of computer memory are DRAM and SRAM. DRAM offers high storage density but requires periodic refreshing, with its development constrained by density and cost. In contrast, SRAM does not require refreshing, provides faster access, but occupies larger cell areas, making it primarily suitable for high-speed caching. Both have been widely adopted in servers, personal computers, and mobile devices, demonstrating excellent performance in latency, bandwidth, and energy consumption. Over the past decades, as fabrication processes have advanced and integration has increased, the number of memory cells per chip has grown exponentially.

At present, flash memory is the dominant storage medium in computers. Solid-state drives (SSDs) store data through electronic components, with internal flash memory chips organized in parallel structures to support simultaneous multi-channel read-write operations [9]. A controller is responsible for data organization, space management, and lifespan maintenance, thereby fully leveraging the advantages of flash memory in terms of low latency and high parallelism.

2.3. Current Status of the Semiconductor Memory Industry

2.3.1. Domestic Industry Landscape

In China, the semiconductor memory market is primarily concentrated in DRAM and NAND Flash. Optical storage and magnetic storage are gradually shifting toward enterprise-level applications, with optical storage experiencing rapid development in recent years and driving overall market growth [10]. In 2020, the market size of China's memory industry reached 322.3 billion RMB, representing an 11.87% year-on-year increase.

With the steady improvement of China's economy and technological capabilities, the country has become the world's manufacturing hub for electronic products. Consequently, production of electronic devices continues to increase, and the demand for semiconductor memory grows correspondingly. In 2019, the market size and growth rate declined, mainly due to U.S. sanctions on China's semiconductor industry. However, the sector gradually recovered afterward, underscoring the necessity of mastering independent technologies and reducing reliance on foreign sources.

Figure 1 Market size and growth rate of China's semiconductor memory industry (2016-2020). The chart shows steady expansion from 2016 to 2018, a decline in 2019 due to external sanctions, and recovery in 2020 with an 11.87% growth, highlighting both resilience and the challenges of foreign dependency.

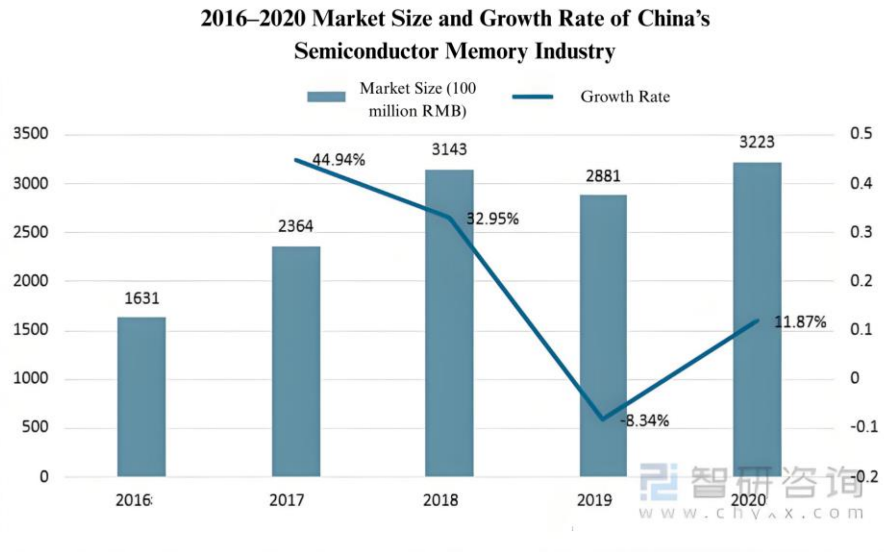

Figure 1. Market size and growth rate of China's semiconductor memory industry (2016-2020).

2.3.2. International Industry Landscape

In 2021, the global semiconductor memory market reached USD 153.84 billion, a year-on-year increase of 30.9%, accounting for 33% of the global integrated circuit market. Within this, the DRAM market was valued at USD 94.19 billion, growing 41.89% year-on-year. According to WSTS, the global semiconductor memory market in 2022 was projected to reach USD 155.46 billion, representing 25.34% of the total semiconductor market.

Figure 2 Global semiconductor memory market size and growth rate (2013-2022). The chart illustrates pronounced cyclical fluctuations: modest growth before 2016, rapid expansion from 2017 to 2018, a sharp contraction in 2019, and a rebound from 2020 to 2022. These shifts underscore the volatility of the global memory sector and its sensitivity to technological demand cycles and international trade dynamics.

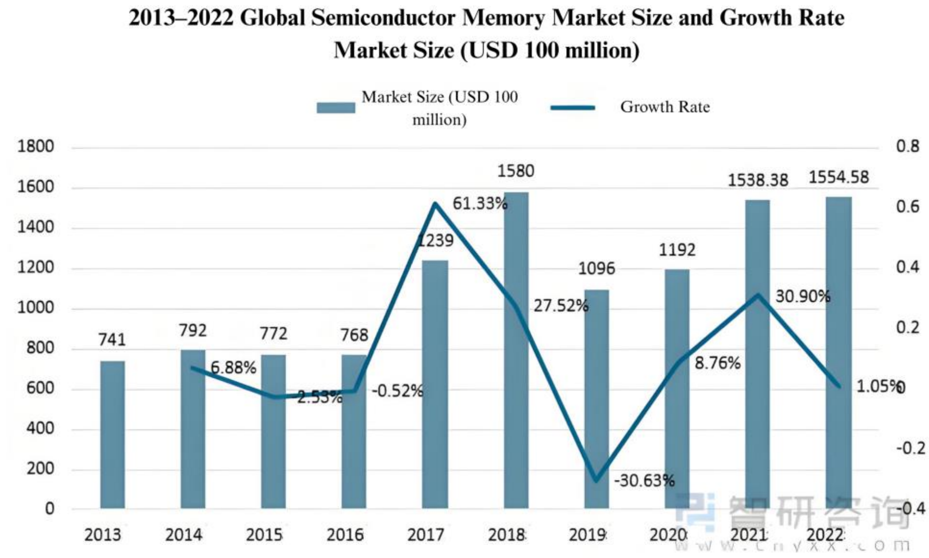

Figure 2. Global semiconductor memory market size and growth rate (2013-2022).

In 2019, the international market decline was even more severe. U.S.-China trade frictions not only disrupted both domestic markets but also exerted global impact. While China's exports of wafers and IC products to the United States were relatively limited and thus less affected by tariffs, companies such as Huawei, Qualcomm, Intel, and Micron were deeply interdependent. As a result, U.S. sanctions also inflicted significant losses on American firms. Some U.S. enterprises were compelled to shift investments to other regions, triggering supply chain restructuring and cost increases.

In facing external restrictions, China must strategically position itself within the global value chain, enhance supply chain security, and strengthen the integrity of its industrial ecosystem. By fostering a virtuous cycle of "technological progress, profitability improvement, talent enhancement," China can accelerate the establishment of a self-reliant and controllable IC industry system.

2.4. Applications and Impacts of Semiconductor Memory

2.4.1. Applications in Everyday Life

In computers, semiconductor memory primarily comprises solid-state drives and main memory.

Solid-State Drives (SSDs): Based on flash memory, SSDs consist of a controller chip, cache chips (absent in some low-end models), and flash memory chips [11]. Compared with mechanical hard drives, SSDs offer advantages such as high speed, lightweight design, low energy consumption, and compact size. However, disadvantages remain, including high cost, limited capacity, relatively short lifespan, and difficulties in data recovery. Despite these limitations, SSDs have entered the mainstream storage market.

Main Memory (RAM): Also known as primary memory, RAM is directly addressable by the CPU and characterized by high access speed [12]. It is composed of RAM, ROM, and cache. RAM allows both read and write operations but loses data once power is cut. ROM, by contrast, is preprogrammed during manufacturing and retains data even when power is off. Cache memory further improves performance. Common specifications for memory modules include 4 GB, 8 GB, 16 GB, and 32 GB.

2.4.2. Influence in the Big Data Era

Memory has become the core component of modern information systems, with DRAM and NAND Flash together forming a market worth over USD 100 billion [13]. With the growth of the Internet of Things (IoT), artificial intelligence, and smart vehicles, storage performance requirements have risen significantly, spurring the rapid emergence of next-generation memory technologies. China is not only catching up in traditional memory domains but is also actively laying out plans for novel memory technologies, thereby gradually improving the industrial ecosystem [14].

Since the 1970s, DRAM has dominated the commercial memory market as its largest segment [15]. The rise of feature phones spurred the growth of NOR Flash, while the PC era expanded the use of NAND Flash. In today's era of intelligence and interconnectivity, market demand continues to increase, raising requirements for speed, power efficiency, capacity, and reliability. Although DRAM offers high speed, it suffers from high power consumption, low capacity, and high cost, and it cannot retain data when powered off. NOR and NAND Flash, meanwhile, are limited by process constraints in speed and density. Consequently, the market urgently awaits new memory technologies with breakthrough performance.

In the security sector, applications such as video surveillance have driven exponential data growth, making traditional storage technologies inadequate. Cloud storage has emerged as an effective solution to large-scale secure storage challenges, supporting initiatives such as "Safe City," "Smart Transportation," and "Sharp Eyes Project," while promoting the evolution of video surveillance toward ultra-high-definition, intelligent, and integrated applications.

The rapid expansion of data volumes further highlights the importance of storage. In 2017, global data volume reached 21.6 ZB, with an annual growth rate of approximately 40%. By 2020, it was projected to reach 40 ZB. In security-related fields in particular, data generated by video surveillance systems has grown linearly, imposing increasing demands for efficient and timely storage and processing.

Figure 3 Evolution of semiconductor memory applications across different eras. The figure illustrates key technological transitions: DRAM dominance in the PC era, NOR Flash during the feature phone era, and NAND Flash in the smartphone era. In the era of AIoT, data centers, and smart vehicles, next-generation memory technologies such as 3D NAND and emerging non-volatile memories are driving the market toward trillion-dollar potential.

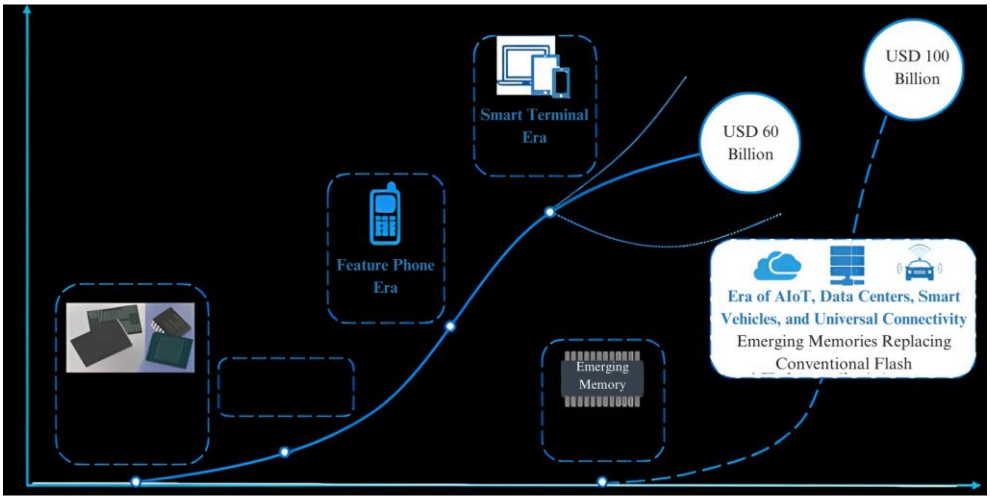

Figure 3. Evolution of Semiconductor Memory Market Across Eras.

2.5. Technical Standards and Intellectual Property Protection

2.5.1. Technical Standards

When the capacity of a single ROM or RAM chip is insufficient, multiple chips must be combined to achieve larger storage capacities. Key indicators for evaluating semiconductor memory performance include:

Storage Capacity: Expressed in terms of word length × bit length or in bytes, commonly measured in KB, MB, GB, and TB. Larger capacity allows greater information storage and enhances system functionality.

Access Time: The time required to complete an operation, such as read time. Shorter access times indicate faster speeds.

Memory Cycle: The minimum interval between two consecutive operations (e.g., reads). This is a critical indicator of main memory speed and is usually slightly longer than access time.

Power Consumption: Reflects energy use and heat generation. Lower power consumption indicates higher efficiency and stability.

Reliability: Measured by mean time between failures (MTBF). A longer MTBF indicates greater resistance to interference and operational stability.

Integration Density: Refers to the number of memory units integrated per chip, typically expressed as bits per chip.

Performance-to-Price Ratio: A comprehensive indicator that balances technical performance with cost, directly determining the practical value of memory products.

2.5.2. Intellectual Property Protection

Patents constitute state-granted exclusive rights for a fixed period and are of critical importance in semiconductor industry competition. They protect technological achievements while also serving as tools for creating market barriers through strategies such as patent portfolio development, licensing, transfers, litigation, and alliances. In recent years, intensifying patent competition, sometimes escalating into "patent wars", has underscored their strategic significance.

In high-technology fields, flexible use of the patent system can effectively restrict competitors and generate significant economic benefits. Increasingly, enterprises are elevating patents to the level of core strategic assets. For instance, Yangtze Memory Technologies (YMTC), a representative domestic IDM, has adopted a strategy of proactive patent deployment during periods of technological breakthroughs. By exploiting areas not yet dominated by international giants, YMTC has effectively pursued "curve overtaking." This approach lowers risks associated with technology sources while enhancing resilience.

Patent strategies should prioritize key technical areas, increase the number of applications while maintaining quality, and expand coverage across different countries and regions in alignment with market priorities and competitive dynamics. Companies should also leverage procedural tools such as divisional applications, priority rights, and continuation applications to broaden protection scope and raise authorization probabilities.

Furthermore, since all new technologies build upon prior ones, enterprises must not only focus on patenting new innovations but also monitor and acquire existing relevant patents through licensing or purchase. This enhances defensive capabilities and ensures the ability to counteract potential litigation threats.

Overall, China's memory industry will remain a "learner" and "catcher-up" for a considerable period but should also strive to become a "contributor" to global progress. Only by mastering core technologies and building a robust intellectual property framework can China secure competitiveness against international giants.

To gain influence in the global industrial landscape, China requires not only advanced manufacturing technologies and large-scale production capabilities but also long-term investment in intellectual property development. This necessitates cultivating professionals skilled in both technology and international IP regulations. Despite high barriers and challenges, China's memory chip industry has already embarked on a path of determined advancement.

3. Production and Sustainable Development of Semiconductor Memory

3.1. Relevant Processes and Technologies in Semiconductor Memory Production

3.1.1. Overview of the Process Flow

Taking solid-state drives (SSDs) as an example, the production of storage chips begins with silicon wafers and involves more than 800 procedures over a period of more than one month. The fundamental process is the layer-by-layer construction of circuit structures through deposition, photolithography, and etching: a photosensitive material is coated onto the wafer surface, ultraviolet light exposure forms the circuit pattern, and chemical dissolution removes the unwanted portions, thereby transferring the circuit design onto the wafer. A 30 cm diameter wafer can yield several hundred chips.

The wafer is then cut into individual chips and packaged. To ensure cutting precision, a layer of adhesive film is applied to stabilize the wafer, after which automated equipment completes the dicing and places the chips into protective housings.

During the circuit board assembly stage, surface mount technology (SMT) is commonly used to rapidly install chips and other electronic components onto printed circuit boards (PCBs). Before SMT, an automated process applies solder paste to the PCB surface to secure the placement of components.

Finally, newly manufactured SSDs undergo rigorous testing to validate their performance and reliability. Only then can a solid-state drive be considered fully manufactured.

3.1.2. Pollutant Emissions in the Fabrication Process

Semiconductor manufacturing involves the use of large quantities of cleaning agents, developers, photoresists, and etching solutions containing organic solvents. These volatile compounds readily evaporate during processing, forming exhaust gases primarily composed of volatile organic compounds (VOCs), accompanied by hazardous pollutants such as HCl, ammonia, and HF, which are difficult to separate and treat. Consequently, semiconductor fabrication is inherently a high-pollution process. Etching and cleaning stages release acidic gases, while solvents such as xylene, acetone, benzene, and carbon tetrachloride, many of them highly toxic, are widely used. Benzene, in particular, has been identified as a Group 1 carcinogen. If pollution control measures fail, such emissions not only endanger workers' health but also cause environmental damage, making stringent waste-gas treatment and waste management systems indispensable.

Primary semiconductor products include silicon wafers, gallium arsenide wafers, and indium phosphide wafers. While silicon dioxide itself is non-toxic, its powdered aerosols can induce pneumoconiosis and lung cancer. Common doping materials such as silane, arsine, and trimethylgallium are toxic, posing both direct health hazards and risks of generating harmful byproducts upon reaction with air or water. Traditional wafer dicing processes also produce dust, similar in risk to other dust-intensive industrial environments.

Semiconductor contaminants manifest mainly in three categories. First are particulate pollutants, originating from air, human activity, and chemical usage during processing. Although some particulates are relatively harmless, those deposited on critical areas can cause fatal device defects. Second are metallic ion contaminants, with sodium ions being particularly problematic due to their high mobility in silicon. Even devices that pass electrical testing may fail during operation due to sodium migration, making sodium control a priority in wafer production. Third are chemical pollutants: unwanted chemical residues may cause uneven etching, form insoluble compounds, or trigger process fluctuations, with chlorine content requiring especially strict control.

3.1.3. Environmental Impacts and Analysis

Semiconductor and photovoltaic industries consume large amounts of fluorinated gases during wafer etching and CVD chamber cleaning. Undecomposed perfluorocarbons

(PFCs) released into the atmosphere exhibit extremely high global warming potential (GWP) and long atmospheric lifetimes. Their life cycle, from synthesis to recycling, creates multiple emission points, with fugitive releases during synthesis, abatement downtime, and cylinder residues identified as the main contributors. Among these gases, SF_6 has the highest GWP, whereas F_2, with a GWP of zero, is considered the most environmentally preferable alternative.

Standardized CO_2-equivalent emissions follow the order $SF_6 > CF_4 > NF_3 >> F_2$, with uncontrolled emissions dominating total contributions. Upgrading facilities to improve abatement efficiency could significantly reduce emissions. Currently, many fabrication plants lack adequate PFC abatement systems, and extended downtime further aggravates emissions.

On-site F_2 generation is regarded as the most sustainable option, offering over 20-fold higher abatement efficiency compared with NF_3 (Figure 4). Although CF_4 has slightly better per-kilogram indicators, its higher flow requirements reduce overall effectiveness. While uncertainties remain in emission estimates, consensus highlights the need to maximize uptime, broaden emission coverage, and improve synthesis and recycling processes. Even with reductions, PFCs will remain a major climate concern, but widespread adoption of F_2 could deliver the most substantial mitigation benefits.

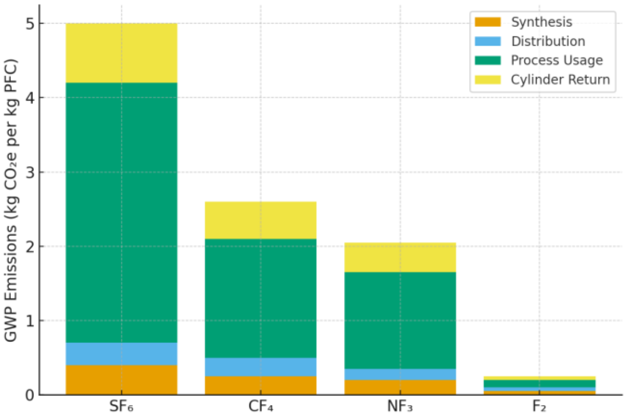

Figure 4. Comparative Life Cycle GWP Emissions of SF_6, CF_4, NF_3, and F_2Across Different Stages.

3.2. Exploration of Novel Sustainable Processes

Taking wastewater from wafer production as an example, the main categories include acidic and alkaline wastewater, ammonia-containing wastewater, fluoride-containing wastewater, grinding wastewater, copper-containing wastewater, and organic wastewater. Different process stages generate different wastewater types, each with distinct pollutant compositions, necessitating separate treatment approaches and source-specific management strategies.

Corresponding treatment processes can be applied to each type. For grinding wastewater and copper-containing wastewater, coagulation-sedimentation methods are commonly employed. By adding polyaluminum chloride (PAC) and polyacrylamide (PAM) to the wastewater and stirring, flocs are formed that facilitate the removal of suspended solids and copper ions. Acidic and alkaline wastewater can be treated through neutralization, adjusting the pH to neutral or to levels suitable for subsequent treatment. Fluoride-containing wastewater is often treated via chemical precipitation, adding lime to generate insoluble calcium fluoride precipitates, followed by flocculants to aid sedimentation and separation.

For wastewater containing volatile or dissolved gases, air stripping may be used, whereby aeration transfers volatile substances into the gas phase for separation. Organic wastewater is typically treated biologically, relying on microbial metabolism under suitable conditions to degrade organic pollutants, thereby rendering wastewater harmless and stable. Depending on oxygen requirements, biological treatment can be categorized into anaerobic and aerobic processes.

4. Limitations of Semiconductor Memory and the Exploration of Optimal Solutions

4.1. Frontiers of International Semiconductor Memory Development (Taking ReRAM as an Example)

Resistive Random Access Memory (ReRAM) is a type of resistive memory that combines the high-speed read-write capability of DRAM with the non-volatility of SSDs, while also offering low power consumption and high speed. It demonstrates remarkable performance in neuromorphic computing, delivering high computational power and low energy consumption, and is regarded as a key candidate for brain-inspired computing. However, ReRAM remains in the developmental stage and faces competition from other emerging technologies such as Phase-Change Memory (PCM) and Ferroelectric RAM (FRAM).

ReRAM has the potential to excel in in-memory computing architectures, supporting bidirectional data flow and enhancing the throughput of large-scale neural networks through modular MPU architectures. Research prototypes at the University of Michigan more than a decade ago highlighted ReRAM's promise in overcoming the bottlenecks of the von Neumann architecture, offering more efficient in-memory computing capabilities for artificial intelligence and edge computing applications.

4.2. Shortcomings and Limitations of ReRAM

Although GPUs have significantly improved memory access speeds, they cannot fully resolve the efficiency challenges of parallel computing, thereby necessitating new computing architectures. While ReRAM holds strong potential, it currently faces three major challenges: (1) its reliance on high-precision analog-to-digital converters for readout circuits; (2) non-ideal issues such as device variability; and (3) nonlinear and asymmetric conductance updates, which reduce training accuracy.

As illustrated in Figure 5, conventional CPUs rely on coarse-grain cores and cache memory but suffer from memory bottlenecks when handling large-scale parallel tasks. GPUs, with finer-grain cores and faster memory access, provide significant improvements but still cannot eliminate data transfer inefficiencies. By contrast, memory processing units (MPUs) integrate computing and storage directly within memory cells, offering device-level parallelism and in-memory computing. This architectural shift highlights why ReRAM-based MPUs are considered a promising pathway to overcome the von Neumann bottleneck, despite their current technological limitations.

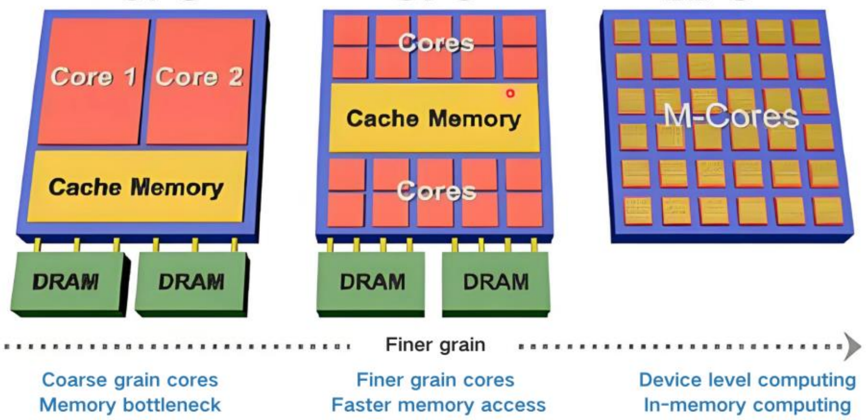

Figure 5. Comparison of computing architectures: CPU, GPU, and MPU.

4.3. Proposed Improvements for ReRAM

To address these issues, several strategies have been proposed. Multi-range quantization and binary neural networks can be adopted to reduce readout circuit complexity; 2T2R architectures or architecture-aware training can mitigate device variability; and hybrid-precision training can enable efficient large-scale network training at lower precision. Meanwhile, other emerging memory technologies such as PCM are also advancing the development of in-memory computing. With the continuous expansion of artificial intelligence, the challenges of improving computational efficiency, reducing data transfer energy consumption, and lowering carbon emissions remain pressing.

Under varying temperature conditions, simple compensation schemes are expected to maintain inference accuracy. Overall, with its high-density non-volatile storage and efficient in-memory computing capabilities, ReRAM is regarded as a powerful tool for overcoming the von Neumann bottleneck. It supports diverse AI algorithms and offers advantages of low power consumption and strong computational capacity. Nevertheless, its immature device fabrication processes and limited market recognition remain obstacles. If technological refinements are accompanied by stronger efforts in promotion and application, ReRAM is likely to secure broader market opportunities in the future.

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