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Integration Technologies of Carbon-Based Materials in Computing-in-Memory Chips

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Abstract. As the traditional Von Neumann architecture computing system with separate storage and computing units no longer meets people's needs, the realization of the integrated storage and computing technology that combines the two is extremely urgent. However, due to the inherent limitations of traditional silicon-based materials, carbon-based materials, with their superior properties, have become the ideal material for realizing the integrated computing and storage technology. At present, this technology is widely applied in fields such as three-dimensional integrated circuits, sensor detection, and digital computing. This review will systematically describe the integration techniques of carbon-based materials in memory-computing integrated chips, providing a detailed analysis of their development and challenges in digital circuits, computing, and sensing applications. Furthermore, this paper explores corresponding solutions and outlines the future prospects for carbon-based compute-in-memory chips. In addition, this study has important theoretical value for promoting fundamental innovations in post-Moore era integrated circuit architectures, providing a feasible material basis and technological pathway for breaking through the traditional bottleneck of computing energy efficiency. At the same time, the potential application of carbon-based computing-in-memory chips in cutting-edge fields such as artificial intelligence also lays the base for the realization of high-performance, low-power information systems.

Keywords: Carbon-based materials, Chip-on-memory integrated circuit, High computing power, Low power consumption

1. Introduction

As Moore's Law gradually loses its effectiveness and the limitations of the von Neumann architecture become increasingly apparent, compute-in-memory technology has emerged as a new focal point. In 2020, a ReRAM compute-in-memory chip emerged, significantly boosting energy efficiency while reducing computational latency [1]. In 2021, the concept of using a tri-level DRAM compute-in-memory architecture to accelerate neural network computations was proposed [1]. In 2022, multi-core integrated chips featuring compute-in-memory technology emerged [1]. To date, integrated storage and computing technology has developed rapidly, with diverse approaches flourishing. For this architecture, traditional silicon-based materials are no longer suitable. First, increasing the chip's operating frequency will further raise the overall power density, thereby increasing the chip's heat generation. In order to limit the heat generation of the chip and avoid exceeding its heat dissipation capacity, which may lead to performance degradation or even burnout, it is necessary to lower the operating voltage to reduce the power density. However, the main principle of traditional silicon-based transistor switches is the hot electron emission mechanism, and the Boltzmann distribution of electrons makes the switching speed of the device unable to be less than 60 mV/dec at room temperature [2]. Due to the dual limitations of off-state current and on-state current, the operating voltage cannot be effectively reduced proportionally [2]. Therefore, it is impossible to effectively control the heat generation of the chip by reducing the operating voltage, and the increase in operating frequency can only be limited to ensure that the power density of the chip does not exceed its heat dissipation capacity. Secondly, when the size of silicon-based materials is reduced to the nanoscale, surface damage or roughness caused by imperfect microfabrication processes will reduce carrier mobility, seriously affecting the electrical performance of the device and disrupting its consistency [2].

To address these issues with silicon-based chips, new materials are needed. Among various new semiconductor materials, carbon-based materials represented by carbon nanotubes and graphene stand out. Carbon-based materials have characteristics such as high energy efficiency, atomic scale, and excellent mechanical flexibility, making them an ideal material to break through the bottleneck of traditional computing architecture and achieve integrated storage and computing technology. At present, carbon-based materials have shown great potential in electronic components (such as memristors), neuromorphic computing, 3D integration, and other fields. For example, carbon nanotube field-effect transistors have superior bandgap and carrier transport characteristics, resulting in high mobility, high current-carrying capacity, and excellent channel electrostatic control [3]. They are widely used in the field of digital circuits [3]. There is also a carbon nanodot memristor, which is an emerging electronic device for artificial biological synapses and human sensory perception systems. It has high uniformity, stability, and precise switching voltage distribution, showing rich application prospects in fields such as brain-like simulation, flexible and biocompatible electronic devices [4].

This review analyzes and summarizes the integration technology of carbon-based materials in integrated memory and computing chips, focusing on the development of integrated circuits in the post Moore era, and explores and prospects the future direction of efficient computing architectures.

2. Development and current status of compute-in-memory chips

The integration of storage and computing includes both near memory computing and in memory computing. Near memory computing uses technologies such as 3D packaging and high bandwidth memory to shorten the distance between memory and processor, and increase data bandwidth. Its essence is actually the use of a storage computing separation mode, while in memory computing completely breaks the limitations of traditional von Neumann architecture and achieves the integration of storage and computing. This article mainly discusses in memory computing chips.

The current development direction of integrated storage and computing chips can be summarized as follows. Firstly, move the integrated storage and computing chip to the sensing end and deeply integrate it with the sensing module, while developing efficient digital analog mixed domain signal processing methods to solve the problems of high latency and high power consumption in signal processing by the sensing chip [5]. This mainly targets wearable devices, IoT devices, and other fields to reduce costs and energy consumption [5]. Secondly, move the storage and computing integrated chip to the cloud, utilizing its advantages of large-scale parallel computing to reduce bandwidth requirements and improve computing power [5]. More than 90% of the basic components of mainstream models such as ChatGPT in Transformer are large-scale matrix operations, which can significantly improve computing power based on this method [5]. Thirdly, integrate hardware units with different computing architectures and functions, and use collaborative heterogeneous integration technology to improve system performance [5]. For example, various heterogeneous architectures have been proposed, such as "near-memory computing + in-memory computing," "analog in-memory computing + digital in-memory computing," "analog in-memory computing + digital accelerators," "digital in-memory computing + digital accelerators," and "in-memory computing + DSP/ISP/CPU" [5]. Fourthly, drive the development of EDA design tools and application tool chains, and promote the mass production and application of integrated memory and computing chips [5]. For example, in the field of artificial intelligence, EDA design tools, development environments, simulators, compilation tools, and intelligent algorithms collaborate to promote market prosperity [5].

Despite the rapid development of integrated storage and computing chips, there are still many difficulties and challenges at present. First, it is difficult to improve the accuracy of analog in memory computing due to the influence of the signal to noise ratio, while digital in memory computing is not affected by the signal to noise ratio, but it requires comprehensive trade-offs in energy efficiency, area and cost, so it is necessary to use digital analog mixed mode to promote the development of in memory computing [1]. Secondly, the in-memory computing chip industry is currently facing the problem of insufficient support for related toolchains, and needs to increase investment to promote the improvement of toolchains [1]. Thirdly, multi-level cross layer collaboration such as device chip process algorithm application needs to be further strengthened [1].

3. Properties and applications of carbon-based materials

As silicon-based integrated circuits approach the limits of physics and engineering, carbon based materials have become one of the alternative paths to replace silicon-based materials. This article mainly analyzes graphene and carbon nanotubes. Carbon nanotubes can be seen as one-dimensional tubular structures formed by curling single-layer graphene in a certain direction. Both have advantages such as chemical stability, high mechanical strength, and good thermal stability, making them ideal materials for preparing electronic devices. The advantages of carbon based electronic devices are as follows. Firstly, carbon based electronic devices have the advantages of high energy efficiency (i.e. high performance and low power consumption). Carbon based devices have a comprehensive performance and power consumption advantage at the transistor level, which is five times that of traditional transistors; If elevated to the level of integrated circuits, the comprehensive performance and power consumption advantage of carbon based integrated circuits can reach 50 times that of traditional circuits. Secondly, carbon based electronic devices have strong tolerance to harsh environments, such as radiation resistance and heat resistance. Thirdly, carbon based electronic devices have a rich variety of device forms and functions. Based on the excellent mechanical flexibility, high transparency, and substrate compatibility of carbon based materials, carbon based devices can achieve various functions such as sensing, storage, logic, and analog circuits. Fourthly, carbon-based electronic devices make it easy to achieve three-dimensional heterogeneous integration. The main challenge faced by 3D integrated circuits is thermal budget requirements, and carbon based devices have low processing temperatures and low operating power consumption, making it easy to overcome this problem. Fifth, carbon-based electronic devices have a shorter process flow and lower cost. The turn-on and turn-off of carbon based transistors are achieved by controlling the injection of charge carriers without a doping process, and they have good immunity to short channel effect during the miniaturization process [6]. A simple planar device process can be used to achieve sub-5 nanometer transistors [6].

Lin et al. from Peking University self-assembled carbon nanotube array materials using DLSA method in 2021 [7]. Through in-depth device structure optimization and process optimization, they successfully manufactured enhanced transistors and multi-stage ring oscillator circuits, achieving a single-stage gate delay of 11.3 ps, surpassing commercial silicon-based devices of the same size [7]. This sufficiently demonstrates the enormous potential of carbon nanotubes in application of high-performance digital circuits. In 2021, a Peking University team led by Xie et al. discovered two types of potential barriers in network carbon nanotube thin films: carbon nanotube junction potential barrier and polymer-wrapped carbon nanotube metal contact potential barrier [7]. Due to the mechanism of carriers tunneling through these two potential barriers under thermal assistance, the resistance caused by the tunneling process increases with decreasing temperature [7]. This changing relationship competes with the law that phonon scattering weakens with decreasing temperature [7]. Therefore, under appropriate bias voltage and channel length, carbon nanotube devices can have high temperature stability, with a current temperature change coefficient of only -0.09%/K, which exhibits approximately one order of magnitude lower than that of single tube and silicon-based devices [7]. Afterwards, in order to further verify the low-temperature stability of carbon-based circuits, Xie et al. also manufactured a fifth-order ring oscillator circuit with an oscillation frequency of up to 1.5 GHz in the temperature range of 300 to 80 K [7]. They found that its performance change was less than 0.5%, thus verifying the enormous potential of carbon-based integrated circuits based on networked carbon nanotube thin films in low-temperature electronic applications [7]. Lu et al. fabricated high-quality metallic carbon nanotubes through the reaction of Fe (C5H5) 2 gas at a low temperature of 550 ° C, with a resistivity of approximately 10-6 Ω• m, a thermal conductivity of approximately 800 W • m-1 • K-1, a Young's modulus of up to 1000 GPa, and a through-hole depth to width ratio greater than 25 [7]. When used as TSV for 3D integrated circuits, it can reduce device temperature by about 15 ° C, improve system reliability by about 10 times, and reduce the holding area of about 80% of the layout and wiring area, fully demonstrating the electrical, dependability, and layout and wiring superiorities of metal bearing carbon nanotubes as through-hole materials for 3D integrated circuits [7]. However, carbon-based 3D integrated circuits are still in their early stages, and there are still issues to be addressed such as device interconnection reliability and heat dissipation in 3D circuits [7]. In addition, in 2020, Peng Lianmao's research group achieved multifunctional detection of biological signals [8]. They used modified carbon nanotubes for selective detection of biomolecules and integrated sensing functions for gene screening and cancer diagnosis on 4-inch substrates, successfully completing the detection and demonstrating the potential of carbon nanotubes in biosensing [8]. It can be seen that carbon-based materials have a very wide range of application prospects in multiple fields due to their excellent properties [8].

4. Integration methods and technical challenges of carbon-based materials in memory-processing integrated chips

Carbon-based materials provide an ideal material foundation for integrated storage and computing chips, mainly reflected in the following aspects. Firstly, carbon-based materials are ideal core materials for synaptic devices. Storage computing integration, especially for neuromorphic computing, often requires electronic devices that simulate biological synaptic behavior, namely memristors. The layered structure and rich functional groups of carbon-based materials make them an ideal dielectric layer for preparing memristors, which can achieve stable and controllable resistance switching behavior [9]. Secondly, carbon-based materials can be used to construct three-dimensional cross arrays. Carbon nanotubes and graphene have excellent electrical and thermal properties, and are atomic-level thin layers that can reduce device thickness to sub-nanometer scales, making them highly scalable and controllable in creating high-density three-dimensional (3D) cross arrays [10]. Thirdly, carbon-based materials are the key to constructing matrix vector multiplication. This kind of calculation is the core optimization goal in the chip. It can achieve a high degree of parallelization, decomposing calculations into a large number of independent multiply add operations; Efficient data reuse can be achieved, significantly reducing the energy consumption and latency of accessing slow external storage; It can also regulate data flow by adopting customized architectures such as dedicated data paths and pulse arrays. By finely coordinating the rhythm of data flow, seamless overlap between computation and data transmission can be achieved, achieving hardware utilization and energy efficiency ratios close to theoretical limits. Carbon based materials can be used to manufacture low-energy, highly integrated hardware required for this computing mode, and are an indispensable part of it.

However, at present, applying carbon-based materials to compute-in-memory chips still faces numerous challenges, such as the difficulty in controlling the cost and purity of material preparation, compatibility issues between carbon-based materials and CMOS process lines, and significant performance fluctuations in carbon-based devices.

5. Applications and development prospects of carbon-based integrated memory and computing chips

Carbon-based electronic technology has demonstrated tremendous application potential across multiple fields, including digital computing, radio-frequency electronics, sensing and detection, three-dimensional integrated circuits, and specialized chips. Carbon nanotubes with ballistic transport properties can carry currents several orders of magnitude higher than conventional metallic wires, making them ideal conductors for nanoelectronic devices and micro/nano circuits [11]. Semiconductor carbon nanotubes can be assembled into field-effect transistors as channel materials. Possessing an outstanding on-off ratio, they can replace traditional silicon-based field-effect transistors and extend the development of Moore's Law [11]. Fluorescent CDs exhibit outstanding luminescent properties and high emission efficiency. The strategy of integrating the photoelectric response of CDs materials contributes to advancing photovoltaic electronic devices toward greater progress in multidimensional applications [4]. Chen et al. and Yang et al. from Peking University employed networked high-purity carbon nanotube films and undoped self-aligned CMOS technology to achieve 100% yield non-inverting gates (inverters), AND gates, NOR gates, and other basic logic gate units, as well as complex sequential logic units such as shift registers, D flip-flops, and T-latches. They even achieved high-performance medium-scale digital integrated circuits like 83-stage ring oscillators, 2-bit multipliers, and 4-bit full adders, all demonstrating rail-to-rail correct logic outputs [7]. Liu et al. who were from Peking University integrated a VCO temperature sensor, carbon-based MOS circuits, a lithium-ion battery, and an antenna onto a flexible substrate using high-performance carbon nanotube CMOS devices. They demonstrated a complete IoT node system featuring sensing, signal processing, wireless signal transmission, and power supply, characterized by very high energy efficiency, super-low dynamic power consumption, and a tunable frequency range of 0.4–1.5 GHz. including the frequency bands which are necessary for NB-IoT or GSM applications. This demonstrates the utilization potentiality of carbon-based digital/analog hybrid integrated systems in the IoT field [7]. The research group led by Dongming Sun at the Shenyang Institute of Metal Research, Chinese Academy of Sciences, has fabricated a flexible display driver circuit comprising over 8,000 carbon nanotube thin-film transistors. This circuit exhibits excellent uniformity (with a pixel yield rate as high as 99.93%) and performance meeting requirements (switching ratio reaching 10^7), demonstrating the uniformity advantages of carbon-based flexible circuits [7].

6. Conclusion

This article summarizes the integration technology of carbon-based materials in storage and computing integrated chips in the post Moore era. Carbon based materials, as the most promising and highly anticipated new semiconductor materials in today's era, have successfully promoted the development of high-performance and low-power carbon based digital circuits, carbon based 3D integrated systems, and carbon based electronic devices based on their advantages of stable chemical properties, strong tolerance, and excellent electrical performance, thereby accelerating the development of integrated memory and computing chips. In the era of rapid development of artificial intelligence, big data, and the Internet of Things technology, the development of carbon-based storage computing integrated chips is an important measure to break through the bottleneck of the traditional storage computing separation mode of the von Neumann architecture computing system. The carbon-based storage and computing integrated chip utilizes the high-performance of carbon-based materials and the integrated architecture of storage and computing, completely breaking the traditional "storage wall" and "power consumption wall", and achieving efficient processing of data in situ. This not only improves computing power efficiency by several orders of magnitude, but also directly drives the explosion of edge intelligence, the Internet of Things, and AI terminals with ultra-low power consumption and ultra-high integration, extending smart devices to all aspects of people's lives. This is of great significance for the development of the digital ecosystem. In the next decade, the carbon-based memory computing integrated chip is expected to take the lead in realizing commercial applications in low-power consumption fields such as wearable devices and smart sensors, and provide core hardware support for miniaturized, real-time edge computing, and promote terminal intelligence to enter a new stage.

References

[1] Guo, X. J. (2023). Research progress and applications of in-memory computing chips. Journal of Electronics & Information Technology, 45(5), 1888–1898.
[2] Xu, H. T. (2021). Research progress and prospect of carbon-based integrated circuit technology. Frontiers of Data & Computing, 3(5), 4–27.
[3] Chen, Z., Chen, J., Liao, W., et al. (2024). Progress on a Carbon Nanotube Field-Effect Transistor Integrated Circuit: State of the Art, Challenges, and Evolution. Micromachines, 15(7), 817.
[4] Zhang, C., Chen, M., Pan, Y., et al. (2023). Carbon Nanodots Memristor: An Emerging Candidate toward Artificial Biosynapse and Human Sensory Perception System. Advanced Science, 10(16), 2207229.
[5] Kang, W., Kou, J., & Zhao, W. (2024). In-memory computing technology: development status, trends and challenges. SCIENTIA SINICA Informationis, 54(1), 16.
[6] Qiu, C., Zhang, Z., Xiao, M., et al. (2017). Scaling carbon nanotube complementary transistors to 5-nm gate lengths. Science, 355(6322), 271–276.
[7] Liu, Y. F., & Zhang, Z. Y. (2022). Carbon based electronic technology in post-Moore era: progress, applications and challenges. Acta Physica Sinica, 71(6), 068503.
[8] Liu, C., & Zhang, Z. (2021). Carbon-based CMOS integrated circuit technology: development status and future challenges. SCIENTIA SINICA Chimica, 51(11), 1457–1473.
[9] Duan, H., Cheng, S., Qin, L., et al. (2022). Low-Power Memristor Based on Two-Dimensional Materials. The Journal of Physical Chemistry Letters, 13(31), 7130–7138.
[10] Zhou, H., Li, S., Ang, K. W., et al. (2024). Recent Advances in In-Memory Computing: Exploring Memristor and Memtransistor Arrays with 2D Materials. Nano-Micro Letters, 16(1), 121.

[11] Lin, Y. N., Ma, L., Yang, Q., et al. (2022). Electron transport properties of carbon nanotubes with radial compression deformation. Acta Physica Sinica, 71(2), 027301.