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Research Progress and Challenges of Two-Dimensional Nanomaterials in the Field of Neuromorphic Devices

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Abstract. In contemporary society, developing more efficient information processing systems has become a critical goal in modern technological advancement. Among emerging technologies, neuromorphic devices, benefiting from their in-memory computing characteristics, hold significant potential to become a breakthrough technology for overcoming current computational bottlenecks. The key to realizing brain-inspired computing lies in the hardware foundation, specifically, neuromorphic devices capable of simulating biological neuron and synapse functions. In recent years, two-dimensional nanomaterials, represented by graphene, transition metal dichalcogenides, and black phosphorus, have emerged as promising materials for neuromorphic devices due to their excellent optoelectronic properties, tunable electrical states, and operational principles that closely resemble those of biological synapses and neurons. By reviewing recent research progress in this field, this article focuses on the applications and challenges of two-dimensional nanomaterials in neuromorphic devices. However, transitioning this technology from the laboratory to large-scale applications still faces multiple challenges, including fabrication processes, integration strategies, and synergistic algorithm architectures. Future advancements will depend on the exploration of new material systems, breakthroughs in three-dimensional heterogeneous integration technologies, and genuine hardware-algorithm co-design. Ultimately, these efforts will drive transformative applications of two-dimensional material-based neuromorphic chips in critical fields such as edge intelligence and biomimetic sensing.

Keywords: Two-dimensional Nanomaterials, Neuromorphic Devices, Neuronal Networks, Optoelectronic Synapses, Artificial Neurons

1. Introduction

Amid the rapid advancement of artificial intelligence technology, traditional computing architectures face energy efficiency bottlenecks when processing massive amounts of data. Computing systems based on the von Neumann architecture, due to the separation of memory and processing units, suffer from data transfer delays and increased energy consumption, leading to the so-called "memory wall" problem. In contrast, the human brain employs a parallel processing mechanism with integrated memory and computation, demonstrating exceptional energy efficiency when performing complex cognitive tasks. This advantage has driven researchers to focus on developing

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novel neuromorphic computing devices that mimic the information processing methods of biological neural networks. In recent years, two-dimensional nanomaterials have emerged as ideal candidate materials for achieving high-performance neuromorphic devices, owing to their unique layered structures, tunable electronic properties, and excellent optoelectronic performance. This paper systematically explores the research progress of two-dimensional nanomaterials in the field of brain-inspired computing, with a focus on analyzing their working mechanisms and performance in artificial synapse and neuron devices. It also provides an outlook on the challenges and future prospects for the development of this technology.

2. Overview of neuromorphic devices

Neuromorphic devices are a type of hardware that integrates principles from biological science and computer science. By mimicking the structure and functionality of the brain, they enable rapid and highly efficient information processing. The core objective of such devices lies in constructing computing systems that possess capabilities analogous to human cognition—such as thinking, memory, reasoning, and learning.

2.1. Working principles of neuromorphic devices

The core working principle of neuromorphic devices is based on two key components in biological nervous systems: neurons and synapses [1]. The connection strength of biological synapses is not fixed but dynamically adjusts according to the timing and frequency of firing in the pre- and postsynaptic neurons. This characteristic is known as synaptic plasticity, which forms the foundation of learning and memory. Electronic devices simulate synaptic weight through their conductance value. External stimuli (electrical pulses, optical pulses) can induce changes in the internal physical state of the device, leading to continuous, analog-like modulation of its conductance. Common physical mechanisms include filament formation, charge trapping/detrapping, ion migration/intercalation, phase change, and others.

2.2. Classification of neuromorphic devices

2.2.1. Optoelectronic synapses

Optoelectronic synapses introduce light as an additional key tuning degree of freedom alongside electrical signals. Compared to traditional electrical synaptic devices, optoelectronic synapses offer high bandwidth and low crosstalk, allowing parallel read and write operations across multiple channels, thereby significantly enhancing information processing speed. Furthermore, optoelectronic synapses can directly preprocess and extract features from optical information (Figure 1), performing partial computational tasks at the sensing end and avoiding data movement, making them ideal devices for vision-based intelligent processing systems. Light can induce unique long-range effects and photogenerated carrier effects, offering possibilities for multimodal learning and complex conditioned reflexes. Based on the roles of light and electricity, optoelectronic synapses can be classified into different types, such as light-modulated conductance, light-generated conductance, and light-coordinated electrical modulation. For example, some optoelectronic synaptic devices based on two-dimensional materials, such as MoS_2 and WS_2, leverage their excellent optoelectronic properties to achieve light-modulated synaptic weights, laying the foundation for building integrated vision systems that combine sensing, memory, and computation.

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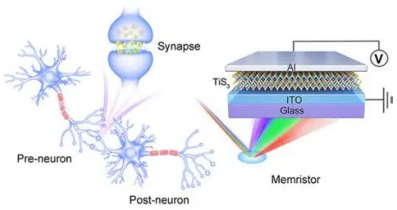

Figure 1. Optoelectronic synapses [2]

2.2.2. Neuronal networks

Spiking neural networks, formed by the interconnection of neurons and synapses, serve as the foundation for achieving complex intelligent behaviors. Challenges at the network level include the large-scale integration of neurons and synapses, efficient spiking encoding and routing strategies, and the implementation of on-chip learning, among others. Based on the physical foundations of the implementation of brain-inspired units, current neuromorphic chips can be primarily categorized into three major types: digital CMOS-based, mixed-signal CMOS-based, and novel principle device-based. Digital CMOS-based neuromorphic chips aim to emulate the behavior of biological units using logic gate circuits.

3. Fundamental properties of two-dimensional nanomaterials

3.1. Structure of two-dimensional nanomaterials

Two-dimensional nanomaterials refer to layered materials with atomic-level thickness in one dimension while extending in the other two dimensions. A typical example is graphene. Graphene consists of a single-layer mesh of carbon atoms, where each carbon atom forms covalent bonds with three neighboring carbon atoms, adopting sp^2 hybridization to create a stable honeycomb-like structure. Other representatives include transition metal dichalcogenides, black phosphorus, and hexagonal boron nitride [3], as shown in Figure 2.

A common feature of these materials is their surfaces being free of dangling bonds, and the layers are held together by relatively weak van der Waals forces, allowing them to be easily exfoliated and form high-quality heterointerfaces. The layered structure of two-dimensional materials gives rise to unique electronic band structures. When the material is thinned down from bulk to a single layer, it often exhibits properties significantly different from those of its bulk form. For example, MoS_2 transitions from an indirect bandgap to a direct bandgap semiconductor, leading to a significant enhancement in its photoluminescence efficiency.

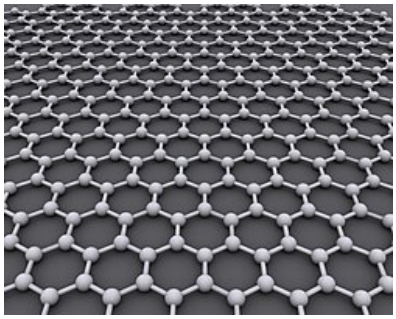

Figure 2. The molecular structure of graphene [4]

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3.2. Physical and chemical properties of two-dimensional nanomaterials

Due to their atomic-scale thickness, two-dimensional materials exhibit distinct physical and chemical properties compared to three-dimensional bulk materials, even displaying unique phenomena that make them ideal candidates for neuromorphic devices.

In terms of electrical properties, the family of two-dimensional materials spans the entire range of electrical types, from metals (e.g., graphene, $NbSe_2$), semiconductors (e.g., MoS_2, WSe_2, BP) to insulators (e.g., h-BN). Graphene exhibits carrier mobilities exceeding 10^5 $cm^2/V \cdot s$ at room temperature, far surpassing silicon, while black phosphorus also achieves hole mobilities of several thousand $cm^2/V \cdot s$. Through methods such as electrostatic doping, chemical doping, layer-number modulation, and strain engineering, the carrier concentration, type, and even band structure of semiconducting two-dimensional materials can be precisely and dynamically tuned.

Two-dimensional materials also possess extremely high Young's modulus and intrinsic strength. At the same time, owing to their ultrathin nature, they demonstrate exceptional flexibility and stretchability, capable of withstanding significant strain without fracture, making them ideal for constructing flexible, wearable neuromorphic chips [5].

Additionally, two-dimensional materials have an enormous specific surface area, making them highly sensitive to external environments (such as adsorbed gas molecules or ions) [6]. This property can be utilized to construct ion-regulated synaptic devices, simulating the role of neurotransmitters in biological synapses.

3.3. Production of two-dimensional nanomaterials

3.3.1. Top-down

Mechanical Exfoliation Method: Repeatedly peeling bulk materials with adhesive tape can yield high-quality monolayer or few-layer 2D material crystals. The samples obtained through this method exhibit the highest quality with minimal defects, making it the preferred choice for proof-of-principle experiments. However, it lacks control over size and position, and the yield is extremely low.

Liquid-Phase Exfoliation Method: Bulk materials are exfoliated in solvents through ultrasonication or ion intercalation, enabling large-scale production of 2D material inks suitable for large-area fabrication processes such as spraying and printing. However, this method tends to introduce defects and contamination, and the resulting flakes are often small in size and non-uniform in thickness.

3.3.2. Bottom-up

Chemical Vapor Deposition (CVD): This method is a key technology for integration and has already enabled the uniform growth of wafer-scale monolayers of materials such as MoS_2 and WS_2 [7]. The CVD process involves chemical reactions and nucleation of precursor gases on high-temperature substrates, allowing for the preparation of large-area, high-quality two-dimensional films. However, challenges such as grain boundaries, defect density, and doping control remain ongoing issues requiring continuous optimization.

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4. Applications of two-dimensional nanomaterials in neuromorphic devices

4.1. Optoelectronic synaptic devices

4.1.1. Application scenarios

Optoelectronic synapses based on two-dimensional materials show great potential in neuromorphic vision systems [8]. For example, by leveraging the photoresponse of materials like MoS_2, the conductance of such devices can undergo potentiation or depression similar to biological synapses when stimulated by light pulses, enabling the "memorization" of optical information in the form of synaptic weights [9]. These devices have successfully simulated learning and memory behaviors such as paired-pulse facilitation (PPF) and the transition from short-term plasticity to long-term plasticity.

Two-dimensional material-based optoelectronic synapses also support multimodal fusion learning. By combining optical and electrical stimuli, more complex associative learning can be achieved within a single device. For instance, using optical signals to represent "conditioned stimuli" and electrical signals to represent "unconditioned stimuli", the device can learn to associate the two through coordinated stimulation.

4.1.2. Existing problems and solutions

The inhomogeneity during the preparation of two-dimensional materials can lead to fluctuations in device performance. Prolonged exposure to light may cause degradation of two-dimensional material properties (such as oxidation or increased defect density). Solutions include optimizing CVD growth processes, developing novel interface engineering and passivation layer technologies to enhance device environmental stability, and using capping layers or substrates to effectively protect two-dimensional materials from environmental interference.

Meanwhile, due to the rapid detrapping of photogenerated carriers, the memory retention time of many optoelectronic synapses based on two-dimensional materials is relatively short. For instance, MoS_2-based devices may exhibit a memory duration of only 9.9 ms. One solution involves artificially creating trap states to delay the recombination process of photogenerated carriers.

4.2. Neuronal devices

4.2.1. Application scenarios

Two-dimensional materials can be used to construct oscillators or threshold switching devices that realize the integrate-and-fire function of neurons. For example, a research team from Fudan University proposed a novel biomimetic neuronal structure based on wafer-scale two-dimensional semiconductor MoS_2 material and DRAM principles, achieving for the first time the synergistic integration of intrinsic plasticity, spiking timing coding, and visual adaptation within a single hardware device.

Coupled oscillatory neuronal networks utilize multiple two-dimensional material neurons connected via resistors or capacitors to generate synchronized or asynchronous oscillations, which can be applied to solve problems such as combinatorial optimization. These coupled oscillators can synchronize or exhibit complex dynamic behaviors, enabling solutions to problems like the shortest path problem.

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4.2.2. Existing problems and solutions

Oscillation frequency and energy consumption are major challenges for artificial neurons. Currently, many artificial neurons have oscillation frequencies much lower than those of biological neurons and suffer from relatively high energy consumption. Proposed solutions include employing high-mobility materials (such as black phosphorus and graphene) to reduce RC delays, scaling device dimensions down to the nanoscale to decrease capacitance and operating current, and exploring new physical mechanisms based on ultrafast and low-power phenomena like ferroelectric phase transitions and spin-transfer torque.

Reliably integrating tens of thousands of two-dimensional neurons and synapses on a single chip presents a formidable challenge. Potential solutions involve advancing wafer-scale transfer and patterning technologies for 2D materials and leveraging their layered nature to explore three-dimensional vertical integration techniques, thereby enhancing integration density. Research indicates that constructing fully 2D material-based heterostructure systems can enable more compact designs for neuronal circuits.

5. Conclusion

This paper systematically reviews the research progress of two-dimensional nanomaterials in brain-inspired devices. In the field of optoelectronic synapses, devices based on two-dimensional materials have successfully simulated various forms of synaptic plasticity and achieved integrated sensing, memory, and computing functionalities. In terms of artificial neurons, the nonlinear characteristics of two-dimensional materials have been utilized to realize the integrate-and-fire behaviors of biological neurons [10]. Despite significant advancements in the study of brain-inspired devices using two-dimensional nanomaterials, numerous challenges remain in transitioning from the laboratory to practical applications: (1) Material Preparation Challenges: The controllable fabrication of wafer-scale, high-quality, uniform, and low-cost two-dimensional materials and their heterostructures is a primary challenge. Current preparation methods struggle to simultaneously achieve large size, high quality, and high yield, necessitating the development of new synthesis and transfer techniques. (2) Device Uniformity and Reliability Challenges: Ensuring consistent performance and long-term stability of each device within large-scale arrays is critical for achieving massive integration. The performance of two-dimensional material devices is highly sensitive to interface states, defect distribution, and environmental influences, requiring effective encapsulation and uniformity strategies. (3) System Integration Challenges: Efficiently integrating brain-inspired devices based on two-dimensional materials with traditional silicon-based CMOS technology and designing compatible architectures and algorithms constitute a systemic engineering problem. Collaborative optimization across materials, devices, circuits, and architectures is essential.

With the coordinated development of materials science, micro-nano fabrication, and computing architectures, brain-inspired devices based on two-dimensional nanomaterials are expected to play a significant role in fields such as edge computing, intelligent sensing, and low-power artificial intelligence. In this broader context, two-dimensional material-based brain-inspired devices are likely to find wider application spaces, ultimately laying a solid foundation for the realization of a true "electronic brain."

References

[1] Wikimedia Foundation. (2025). Graphene, March 5. Wikipedia. https: //zh.wikipedia.org/zh-cn/%E7%9F%B3%E5%A2%A8%E7%83%AF

DOI: 10.54254/2755-2721/2026.MH31284

[2] Toshiyuki Oda, Haruaki Yanagisawa, Takeyuki Wakabayashi. (2020) Cryo-EM structures of cardiac thin filaments reveal the 3D architecture of troponin. Journal of Structural Biology, Volume 209, Issue 3, 1 March, 107450.
[3] Xinfeng Ouyang, Shuo Duan, Jiujiang Ji, Yunpeng Liu, Wendi Tian, Kangmin Niu. (2025) Study on the compressive strength of carbon fiber reinforced polymer composites–a lesson learned from composite structure design for large commercial aircraft. Advanced materials technologies, 06 June.
[4] Lei Liu, Ziqiang Cheng, Bei Jiang, Yanxin Liu, et al. (2021) Optoelectronic Artificial Synapses Based on Two-Dimensional Transitional-Metal Trichalcogenide. ACS Applied Materials & Interfaces (IF 8.2), 06-25.
[5] Li, D., & Gui, Y. T. (2024). The seventy-two transformations of two-dimensional materials. ScienceNet.cn Blog, March 18. Retrieved from https: //wap.sciencenet.cn/blog-3563286-1427395.html
[6] Shuiyuan Wang, Chunsheng Chen, Zhihao Yu, et al. (2018) A MoS2/PTCDA Hybrid Heterojunction Synapse with Efficient Photoelectric Dual Modulation and Versatility.
[7] Park, S., Naqi, M., Lee, N., Park, S., Hong, S., & Lee, B. H. (2024). Recent advancements in 2D material-based memristor technology toward neuromorphic computing, November 29. Micromachines. https: //pmc.ncbi.nlm.nih.gov/articles/PMC11676942/
[8] Kang Yin, Dongmei Li, Qingbo Meng. (2022) Copper-zinc-tin-sulfur-selenium thin film solar cells [J]. PHYSICS, 51(6): 405-412.
[9] MC, H. S. M. V. (n.d.). Two-dimensional materials for brain-inspired computing hardware. Chemical reviews. https: //pubmed.ncbi.nlm.nih.gov/39745782/
[10] Bochen Zhao, et al. (2025) Bioinspired gas-receptor synergistic interaction for high-performance two-dimensional neuromorphic devices. Matter, Volume 8, Issue 4, 102044.