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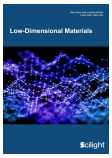

Perspective

Spatio-Temporal Confinement in Two-Dimensional Channels for Neuromorphic Computing

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Abstract: Graphene oxide (GO), with its unique two-dimensional structure, adjustable functional groups, and tunable nanofluidic channels, has emerged as a promising platform for bio-inspired neuromorphic computing. This perspective explores the structural and functional analogies between GO membranes and biological ion channels, emphasizing GO's ability to support selective ion transport, stimuli-responsive behavior, and synaptic plasticity. Recent advances in material engineering and device integration have enabled GO-based artificial synapses, including memristors and ion-gated transistors, to emulate key neuronal features such as excitatory postsynaptic currents, paired-pulse facilitation, and spike-timing-dependent plasticity with sub-millisecond response times and picojoule-level energy consumption. Moreover, the incorporation of GO with polymers, quantum dots, and semiconductors has facilitated multimodal control via electric, optical, and chemical inputs. Together, these developments position GO as a powerful material system for future neuromorphic devices that operate in aqueous and dynamic biological environments, paving the way toward brain-inspired hardware, neuroprosthetics, and intelligent biointerfaces.

Keywords: 2D materials; graphene oxide; artificial synapse; nanofluidics; neuromorphic computing

1. Introduction

Nanochannels and nanopores contribute to non-linear transport mechanisms, rapid fluid movement, and asymmetrical ion transport [1,2]. Two-dimensional (2D) materials with nano-confined interlayer spaces narrower than the Debye length of an electrolyte are currently being developed. These materials can efficiently generate net directional ion currents by attracting counter-ions via surface-charged nanofluidic channels. Graphene-related materials, particularly graphene oxide (GO), offer an innovative opportunity due to their 2D structure and adjustable permeability [3,4]. They represent a new category of membranes with swift water transport and selective ionic and molecular sieving properties, making them ideal for water treatment applications. GO has indeed become a leading platform for nanofluidic applications [5,6]. Inspiration for these membrane materials has been drawn from protein channels like aquaporins, known for their rapid water transport and ion selectivity. Specifically, the sub-nanometer regime exemplifies an extreme case of nanoscale confinement, mirroring conditions observed within the restricted dimensions of biological systems. Given that sub-nanometer conduits are integral components of GO-based lamellar membranes, insights gleaned from these studies may guide the creation of new lamellar membranes for a variety of applications. Considering these points, it is intriguing to explore the potential use of GO in biology, with a particular focus on neuroscience.

2. Structural Similarity between GO and Membrane Proteins

The structural resemblance between GO and membrane proteins presents an interesting aspect (Figure 1). Similar to proteins that comprise diverse aromatic side chains and functional groups, GO possesses a blend of aromatic domains (sp^2 clusters) and a range of oxygen functions (sp^3 C-O matrix). Quantitative study based on fluorescent labelling methods showed that carbonyl, carboxyl and hydroxyl concentrations on the surface of GO are 6.70×10^{20}, 32.49×10^{20} and 19.20×10^{20} groups/g respectively [7]. Moreover, both GO and proteins carry negative charges. The ion channel's transmembrane domains form sufficiently hydrophilic pores to enable ion passage. GO films demonstrate superior water stability compared to other 2D materials due to their strong negative charge and crosslinking facilitated by cationic metals. For example, GO dispersed in water remains well-stabilized for up to 8 weeks, whereas 2D black phosphorus reacts with water and degrades within minutes [8,9]. The similarity in functional groups, charge distribution, and stability enable GO to replicate neuromorphic behaviors.

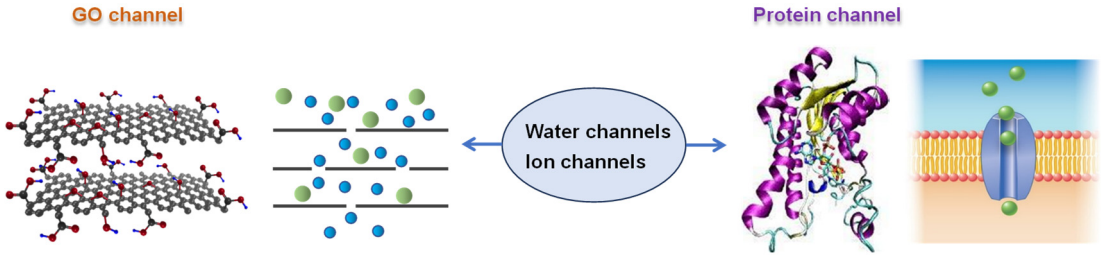

Figure 1. Phenomenological analogy (macroscopic) of GO channels vs. protein channels: water channel, ion selectivity (steric hindrance, electrostatic, cation-π interaction, coordination, dehydration).

Drawing from this structural congruity, integrating nanofluidics and bionics with GO appears a promising strategy (Table 1). This could be achieved by using GO in the roles of aquaporins or even ion channels for neuron signal transduction. Here, GO mimics the water and ion transport functions of membrane protein channels, which are central components in synaptic signal transduction for biological systems. In these systems, ions act as charge carriers and the transport of substances across the membrane forms an essential process underpinning normal life functions. This process heavily depends on the function of transmembrane proteins channels. Transmembrane proteins reside within cell and organelle membranes to sustain normal cellular functions and to facilitate key physiological activities such as synaptic signal transduction, energy conversion, and metabolism. For example, action potential transmits information across cell membranes based on the modulation of ionic conductivity in ion channels of membrane proteins, which is both time- and voltage-dependent, leading to well-coordinated and timely physiological responses. Recent studies have begun to leverage this structural analogy to create GO-based nanochannels that functionally mimic protein channels [10]. Such bio-inspired ion gating in GO underscores its capacity to replicate the selectivity and regulatory functions of membrane channels. For instance, The GO-polyethyleneimine membrane with ~100 nm thick demonstrated selectivity ratios of 33.8, 27.0, and 21.9 for K^+/Mg^{2+}, Na^+/Mg^{2+}, and Li^+/Mg^{2+}, respectively [11]. Furthermore, material tuning strategies—ranging from the introduction of specific functional groups to partial reduction or composite formation—allow researchers to adjust GO's surface charge and hydrophilicity. For instance, GO functionalized with a peptide motif exhibits the capacity for selective ion recognition and transport, using the peptide's ion-binding affinity to achieve filtration of a target ion. These advances highlight how chemical engineering of GO can yield improved bio-inspired performance in ion sieving, directly mirroring the sophisticated selectivity of biological channels.

On another note, the biomedical domain places substantial value on stimuli-responsive materials for their adaptability to various conditions. These materials demonstrate immense potential in adjusting their behavior when exposed to external or internal factors like pH, light, electric field, magnetic field, and temperature. Their effective channel size and specific functional groups, akin to biological ion channels, can significantly improve ion selectivity at concentrations that equal or exceed those of biological ion channels.

Owing to their superior biocompatibility, GO materials have been extensively used in stimuli-responsive applications and biomedical fields, including biosensors, therapeutics, and tissue engineering for decades. GO demonstrates no toxic effects on human fibroblasts when treated at doses below 20 μg/mL for up to 6 days [12]. Additionally, NIH-3T3 fibroblasts cultured on GO-coated substrates showed high biocompatibility and enhanced gene transfection efficiency [13].

Table 1. Phenomenological analogy (macroscopic) of cross-membrane transport modes in GO membranes vs. cell membranes: passive transport [simple diffusion (hydrophobic, small molecules), facilitated diffusion (hydrophilic, big molecules)] and active transport (ions/protons).

Function		GO Membrane (Solid)	Cell Membrane (Fluid Mosaic)
Passive transport (Energy free)	Simple diffusion	Pore/2D channel Steric hindrance	Lipid bilayer Lipid soluble, nonpolar, small polar molecules gases (O_2, CO_2), fatty acid
	Facilitated diffusion	Pore/2D channel Function groups	Protein channel Channel mediated: gated, leak Ions Carrier mediated: polar molecules (glucose, amino acid)
	Osmosis	Pore/2D channel Ultrafast transport	Aquaporin Water
Active transport (Energy driven)		Pore/2D channel Nanofiltration Desalination (reverse osmosis)	Carrier proteins Primary: ion pumps (Na^+/K^+ pump) (Uniport, use ATP, against concentration or electrochemical gradient) Secondary: co-transport (symport), counter-transport (antiport) Bulk (Vesiclular) transport: exocytosis, endocytosis, phagocytosis

3. From Materials to Synapses

Cell transport in the nervous system is integral to cell signaling. A synapse, a junction between two neurons, allows for the transmission of nerve impulses and enables communication across various sections of the brain and body. This junction is critical for information processing and behavior regulation. Building on the similarities between GO and membrane proteins, there has been growing interest in using GO-based devices to simulate synapses, with the goal of enabling complex neuromorphic computing.

The phenomenon wherein synapses modulate their strength in response to neural activity and experience is termed synaptic plasticity, which is governed by presynaptic action potentials. These potentials can induce an influx of Ca^{2+} and trigger the release of either excitatory or inhibitory neurotransmitters, leading to the strengthening or weakening of information transmission. The processing of assorted presynaptic pulses, characterized by differing amplitudes, durations, frequencies, and numbers, culminates in the emission of diverse current signals. This process, known as spike-dependent plasticity, enables the neuronal system to adapt and learn. GO possesses potential for realizing synaptic plasticity, as it features nanometer-scale interlayer channels (ranging from 0.7 to 1.4 nm) with functional groups and charges, similar to biological ion channels. This unique structure enables GO to exhibit ion selectivity and stimuli-responsive behavior. One of the challenging applications is harnessing the highly selective ion transport and stimuli-responsivity in GO to create artificial synapses with synaptic plasticity. Devices such as ion field-effect transistors or memristors, designed for spiking neural networks, hold promises for achieving this goal [14–16]. The objective is to precisely manage ions or neurotransmitters through a variety of materials and structures, with an aim to pinpoint specific ionic signals capable of interacting with and regulating biological processes within the intricate aqueous environment. Encouragingly, recent studies have begun to realize such GO-based synapses in hardware; for example, GO thin films have been employed in transistor devices to emulate synaptic plasticity, showing voltage-dependent excitatory postsynaptic currents and repeatable short-term memory behavior. These initial demonstrations validate the concept of using GO to modulate ionic and electronic signals in devices, as will be detailed in later sections. Furthermore, these behaviors enhance the performance of GO-based synapses in temporal feature extraction and the processing of spikes in artificial neural networks.

4. Beyond the Phenomenological Models

At present, bionic materials intended to accomplish the aforementioned functions are largely based on phenomenological models. There have been no instances of simulating synaptic function and generating action

potentials at a fundamental level. Gradov and colleagues explored the viability of graphene and its derivatives as biomimetic membrane materials [17,18]. They examined the prospect of modeling ion channel function and scrutinized the physical mechanisms governing the selective permeability, transport, catalytic, sensing, and electrogenic properties of cell membranes using graphene-based structures. Notably, biomimetic membrane materials do not necessarily need to replicate the soft matter properties or structural components of cell membranes, such as their form, dimensions, or scale. Instead, these materials can take on a 2D structure. Much like a liquid crystal, the cell membrane displays flow dynamics and directional order aligned in parallel. Analogously, while the GO film is in a solid state, it retains liquid crystal properties. The plasma membrane can even be mimicked using a solid-state polymer or a composite membrane of GO and lipid, with water and ion channels confined. The objective is to emulate the ion transport and selectivity of biological cell membranes by appropriately configuring nanopores, horizontal channels, and vertical channels on GO. Two methods have been previously investigated: embedding artificial water channels in a copolymer matrix, or using a mechanically robust inorganic material as a confinement matrix.

Building upon this foundation, researchers have started to translate these models into working prototypes. A recent example is the development of a bioinspired neuromorphic artificial gustatory system that employs reconstructed layered GO membranes as ionic devices [19]. In this system, multiple GO layers within a nanofluidic cell not only sense chemical stimuli (different taste molecules in solution) but also perform reservoir computing for signal processing. The GO membrane channels serve as ionic memristors that encode flavor information into electrical signals which are then analyzed by a machine-learning algorithm. By combining the sensing and computing functions of taste perception into a single moist-environment device, it overcame a major limitation of earlier "electronic tongue" designs. According to the authors, this approach holds promise for restoring or augmenting lost sensory functions. This demonstration goes beyond phenomenological modeling–it shows GO actively participating in a neuromorphic computation under biologically relevant conditions.

The comprehensive neuron conduction process can be further dissected into components. This includes neurotransmitter reception through biosensors, synaptic plasticity via spike-timing-dependent plasticity (STDP) (which involves a Ca^{2+} channel at the pre-synapse and ligand-gated ion channels at the post-synapse), and action potential generation through Na^{+}/K^{+} channels and pumps. Ion selectivity is a primary factor to consider in designing such biomimetic systems. Large ions might be hindered due to steric effects, allowing small ions to pass through. Conversely, isolating small ions and permitting only large ions or a single ion type to traverse necessitates further interactions, such as functionalization, coordination, and electrostatic interactions. GO functionalized with a peptide motif, as noted above, exhibits the capacity for selective recognition and transport. By leveraging the ion-binding affinity of the peptide, selective ion filtration capabilities can be achieved. The resulting GO membranes have demonstrated impressive selectivity towards a specific ion of interest. In a similar vein, employing positively charged functional groups on GO has proven to fine-tune ionic transport: an amino-modified GO membrane was shown to facilitate Cl^{-} transport while excluding multi-charged anions in mixed electrolytes. This chemically gated selectivity, reminiscent of biological ion pumps and channels, underscores the importance of material functionalization in achieving bio-like ion discrimination. Ag/GO/fluorine-doped tin oxide-based device exhibits STDP learning behavior with conductance changes that depend on the relative timing, similar to biological synapses [20]. A memory window of $R_{OFF}/R_{ON} = 34$ is observed under a pulsed bias in Ag/GO/fluorine-doped tin oxide-based device, with stable analog switching maintained over 120 DC sweeping cycles. These modifications highlight the potential of GO in constructing artificial synapses and enhancing the performance of artificial neural networks.

Vesicles: Modified GO nanoflakes have been shown to influence presynaptic vesicle release both in vitro and in vivo (Figure 2a) [21,22]. Interactions between GO and cell membranes can mimic extracellular mechanical signaling at the nanoscale, thus facilitating the release of micro-vesicles. This positions GO as a novel tool for investigating the physics underpinning vesicle release. Extending this concept, recent in vivo experiments have demonstrated that GO can actively modulate synaptic activity [22]. In a rat model of post-traumatic stress disorder (PTSD), a single injection of small GO sheets (20 μg/mL, 30 s) into the lateral amygdala following a traumatic event prevented the expected potentiation of glutamatergic synapses and induced a remission of PTSD-related anxiety behaviors. Mechanistic studies revealed that GO nanosheets reduced the probability of presynaptic glutamate release, thereby impairing the development of long-term synaptic strengthening in the amygdala circuits. These findings suggest that direct nanomaterial interaction at synapses can downregulate excitatory neurotransmission, highlighting GO's potential as a nano-biomedical tool to modulate vesicle release and synaptic plasticity in the brain.

Ligand-gated channels (receptors): A field-effect transistor (FET) biosensor based on GO, functionalized with a synthesized glutamate receptor, allows for real-time monitoring of glutamate release. Impressively, this

receptor-decorated GO transistor demonstrated femtomolar-level sensitivity to glutamate, enabling it to detect minute neurotransmitter release events from cultured neurons in real time (Figure 2b) [23]. The detection limit was determined to be 1 fM. Additionally, a significant drain current change rate of approximately 0.41% was observed with 10 pM Glu and 0.70% with 100 pM Glu, demonstrating the high selectivity of the FET sensor for Glu molecules. The immobilized metabotropic glutamate receptors on the GO surface endowed the device with specific binding sites for glutamate, translating binding events into conductance changes. This design offers a novel approach to customizing GO selectivity for specific molecules, mimicking the function of synapses in detecting neurotransmitters and providing a tool for studying neural communication dynamics with high precision.

Action potential: In the context of a spiking neural network, the electrical signal is actively transported along the axon (Figure 3). This long-range transmission of ionic currents can be conceptually mimicked by conductive or ionic pathways in GO-based devices (for instance, ion-conducting channels that propagate a potential). GO-based neuromorphic devices exhibit a memristive effect at experimentally relevant frequencies (f~100 Hz) and voltages (U~0.1 V), resulting from the strong nonlinear-effects in ion transport across the quasi-two-dimensional slits of GO. These devices also consume low energy (~0.7 pJ per spike), making them more efficient compared to other neuromorphic computing devices [24]. While GO structures can facilitate rapid ion motion with low energy consumption, replicating the regenerative, all-or-nothing propagation of a true action potential remains an ongoing challenge. Some research efforts are investigating whether cascaded GO memristors or transistor arrays could emulate the sequential ion channel openings that underlie an action potential. Ag/GO/Au array devices exhibited threshold resistive switching with enhanced performance, including low leakage current (≈10~12 A), low operation voltage (~0.3 V), high endurance (>12,000 cycles), and electro-synaptic plasticity (Figure 2c) [25]. However, a full biomimetic action potential in GO hardware has yet to be realized.

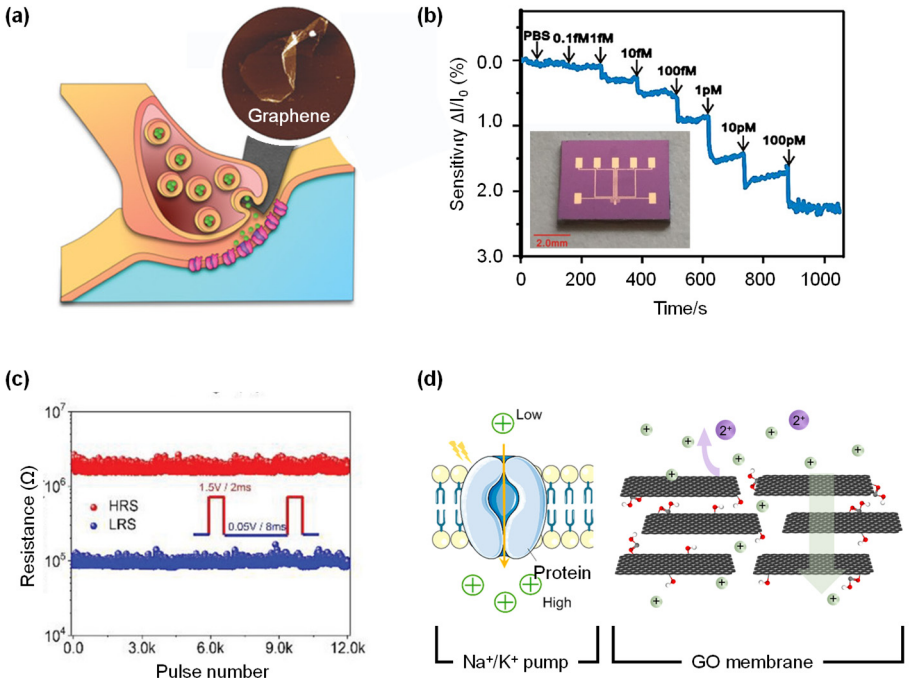

Figure 2. GO and related biological structures. (**a**) Modified GO nanoflakes influencing presynaptic vesicle release. Reprinted with permission from Ref. [21]. Copyright 2016 American Chemical Society. (**b**) Receptor-decorated GO transistor demonstrating femtomolar-level sensitivity to glutamate. Reprinted with permission from Ref. [23]. Copyright 2019 American Chemical Society. Inset: Optical image of one GO transistor chip. (**c**) Ag/GO/Au array devices exhibiting high endurance. Reprinted with permission from Ref. [25]. Copyright 2024 Wiley-VCH GmbH. (**d**) Comparison of Na^+/K^+ pump (left) and GO membrane for ion separation (right). Reprinted with permission from Ref. [26].

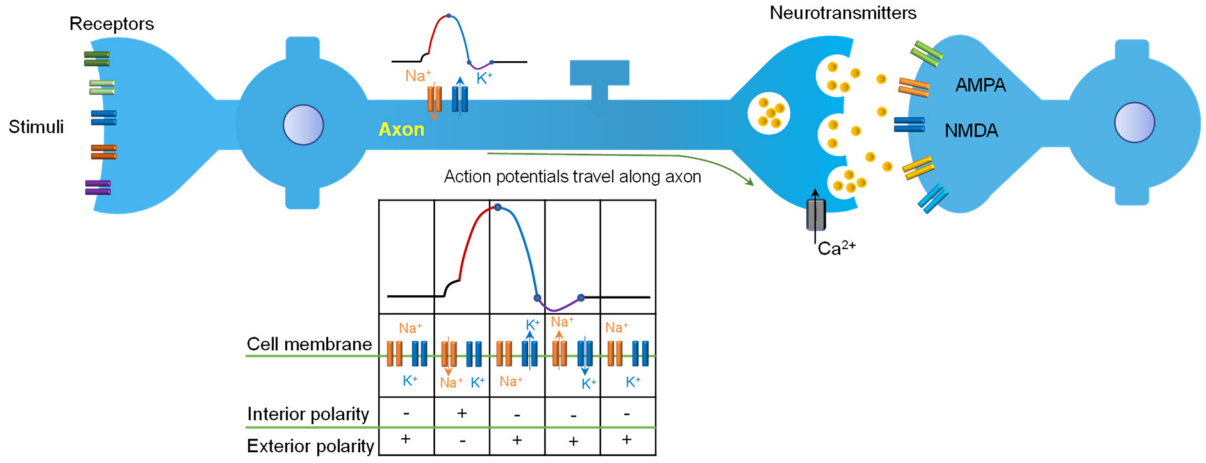

Figure 3. The whole process of information transports along neurons.

Ion pumps: Establishing a proton (H^+) pump is relatively simple in artificial systems, but the creation of a Na^+/K^+ pump presents a substantial challenge. The $3Na^+/2K^+$ exchange cycle is fundamental to biological systems, presenting structural differences when compared to existing ion separation GO membranes (Figure 2d) [26]. Although artificial ion channels with various passive transport properties have been developed, it remains a significant hurdle to accomplish intelligent ion transport at the high level seen in biological ion pumps. One of the key challenges for GO-based systems is achieving high ion selectivity for diverse monovalent cations, as GO membranes typically exhibit similar selectivity for smaller ions like Na^+ and K^+. Further optimization of the functional groups and surface charge distribution in GO is necessary to enhance selectivity and prevent undesired ion flow. The development of alternative synthetic approaches to produce GO derivatives with controlled chemical structures, morphologies, and tailored ion transport properties has become increasingly important. Additionally, the combination of GO with enzyme functionalization may offer a promising solution. Moreover, no GO-based system has yet succeeded in replicating the active, ATP-driven pumping action of the Na^+/K^+ pump, and current GO-based systems still require external energy sources to drive ion transport. Some conceptual strategies involve asymmetrically charged GO membranes or electro-osmotic coupling to preferentially drive certain ions against a gradient, but achieving the coordinated, energy-coupled ion exchange of the real pump is still beyond current technology. Continued advances in nanofluidic design and perhaps coupling GO with enzymatic or catalytic elements will be needed to approach the sophistication of biological ion pumps.

5. Towards Neuromorphic Computing

Neuromorphic computing is deeply rooted in the replication of natural neural networks. Besides the numerous mathematical approximation and modeling techniques aimed at simulating brain operations (Table 2), direct replication of the functional synaptic connectivity map of a biological brain presents a novel approach to constructing biologically accurate neural networks. The use of artificial synapses, and their potential applications in logic operation, image/pattern recognition, and proposed designs for hardware neuromorphic computing devices, are garnering increasing interest [27–29].

Table 2. High-level realization of neural transport.

Sensing-Perception			**Learning-Memorizing-Reasoning**			
Receipt	Integration	Transmission	Computing & Coding	Computing & Coding	Integration	Transmission
Receptor	Soma	Axon	Synapse	Dendrite	Soma	Axon

Recent advances in device engineering have started to translate GO's unique spatio-temporal ion confinement properties into tangible neuromorphic hardware components. The confined space forces ions to pass through a restricted, 2D channel, thereby strongly influencing their transport dynamics. As ions migrate through the confined spaces of GO, they redistribute at the GO interfaces, resulting in ion accumulation or depletion, which is a key feature underlying synaptic plasticity. Moreover, the confined space and electrostatic interactions between ions and functional groups on GO surface lead to nonlinear changes in ion conductivity. This nonlinearity is essential

for simulating synaptic weight changes, which are central to the learning process in neuromorphic systems. By integrating GO into functional devices, these contributions of spatio-temporal lead to synaptic behaviors, enabling bio-inspired neuromorphic functionality. In particular, two-terminal memristors incorporating GO have achieved notable performance as artificial synapses. One example is a lateral memristor structure created by direct laser reduction of GO between Pt electrodes; this device switches at an ultra-low energy consumption of around 200 nW and can emulate multiple synaptic states in an analog fashion [30]. When organized into an array for reservoir computing, these memristors demonstrated pattern-recognition capabilities. The unique spatio-temporal ion confinement properties in GO can be further enhanced by inserting suitable buffer layers, leading to bio-inspired neuromorphic behaviors. One memristive design employs a layered GO/pyridinium/GO structure, in which an organic pyridinium ion is intercalated between GO sheets [31]. In conventional memristors, the abrupt switching occurs due to uncontrolled ion migration, leading to random and overgrown conductive filaments, potentially causing device failure. In contrast, the pyridinium layer in GO/pyridinium/GO acts as a molecular buffer that intrinsically controls the formation of conductive filaments during switching. As a result, the memristor's resistive transitions become progressive and bidirectionally tunable rather than abrupt, allowing for gradual increases or decreases in conductance that closely resemble biological synaptic weight updates. All essential synaptic behaviors–including analog long-term potentiation/depression, excitatory postsynaptic currents, paired-pulse facilitation, and even a "learning-forgetting-relearning" cycle–have been replicated in this GO/pyridinium device. Notably, the device can be stimulated with low-voltage, short pulses (on the order of a few volts and milliseconds), indicating fast switching speeds and low energy operation compatible with neuromorphic computing requirements. This example illustrates how tailoring the material composition of GO-based memristors (through composite formation or doping) yields improvements in linearity, stability, and speed that are crucial for high-precision neuromorphic systems. After composition modification, GO-based artificial synapses exhibit smoother output responses during learning, resulting in more accurate mappings between input patterns and output classifications in artificial neural networks. Moreover, GO-based resistive switching memory indicated a memory window of 20 and presents reliable retention characteristics of 10^4 s and 50 reproducible write-read DC cycles without degradation [32].

Beyond resistive memory elements, three-terminal GO-based synaptic transistors have also been demonstrated [33]. The device showed clear neurosynaptic behaviors: it produced excitatory postsynaptic current (EPSC) spikes upon gating, with the spike amplitude and duration dependent on the applied pulse magnitude and width. It was further able to emulate short-term plasticity phenomena such as paired-pulse facilitation and paired-pulse depression, meaning the conductance change from a second stimulus was influenced by the memory of the first. Impressively, a form of spike-voltage dependent plasticity was observed, analogous to biological synapses where the change in synaptic strength depends on the voltage or timing of spikes. The device also showed favorable repeatability of these plasticity behaviors, underscoring that GO-based transistors can reliably mimic synaptic dynamics in hardware. Such ion-gated transistors, which have indicated synaptic behaviors based on GO, open up avenues for building large-scale neuromorphic circuits with fine-tunable synaptic weights.

Crucially, many GO-based synaptic devices inherently support multi-modal control, reflecting the fact that biological neurons respond to a variety of stimuli (electrical signals, neurotransmitters, light in some cases, mechanical forces, *etc*.). Moreover, GO-based memristors are attractive for flexible and biocompatible electronics due to their low cost, eco-friendliness, and mechanical flexibility. By blending GO or its derivatives with organic polymers, researchers have created soft memristive devices that can bend or stretch while maintaining synaptic functions–an important step toward implantable or wearable neuromorphic circuits. These diverse strategies, incorporating GO with semiconductors, quantum dots, and polymers, underscore the versatility of GO as a platform for multi-modal and hybrid neuromorphic devices. Electrical, optical, chemical, and even thermal controls can be integrated into GO-based architectures, bringing us closer to mimicking the full complexity of biological neural processing in hardware.

It is therefore with confidence that we look forward to potential breakthroughs with GO particularly in the areas outlined below (Figure 4). Materials engineering plays a foundational role in the development of GO-based neuromorphic systems. Structural modifications to the functional groups, charge distribution, and interlayer spacing in GO membranes will significantly influence ion transport through GO channels, thereby driving the neuromorphic behaviors of GO. It is crucial to emphasize the structural and functional analogies between GO membranes and biological ion channels to support selective ion transport, stimuli-responsive behaviors, and synaptic plasticity in GO-based systems. Furthermore, GO-based devices offer promising opportunities for customization to replicate various biological structures and phenomenon. Notable examples include: human touch simulation; application in Ca^{2+} transport and vesicle release; usage in Na^+ and K^+ ion channels and Na^+/K^+ pump; simulation of synaptic signal transmission (for instance, AMPA/NMDA, short-term/long-term memory); modeling

of excitatory postsynaptic potentials (EPSP) and inhibitory postsynaptic potentials (IPSP); generation and transmission of action potentials; simulation of aquaporins; feedback and drive of nerve signals (like acetylcholine (AChE)); and simulation of ATP function (*e.g.*, proton transport). When integrated as arrays or groups, these devices are expected to exhibit enhanced neuromorphic performance, improving their potential for scalable applications. Scalability, integration with CMOS platforms and biological environments, and energy performance remain challenging in terms of GO-based neuromorphic systems. Mimicking the function of brain and body presents an effective solution to address these challenges.

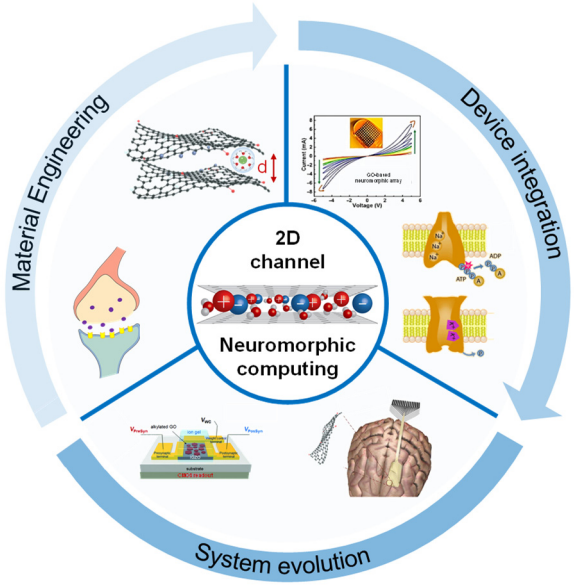

Figure 4. Developing roadmap of 2D channels for neuromorphic computing.

6. Summary and Outlook

In conclusion, graphene-based biomaterials possess the potential to transform the realm of neuromorphic applications by introducing fresh opportunities to mimic the structure and function of neural tissues [34]. Looking forward, there are several key directions that will further advance the application of GO-based neuromorphic devices.

Materials modification. Functionalizing and hybridizing are essential in exploring the neuromorphic potential of GO. Combining GO materials with other advanced materials, such as polymers and nanoparticles, will pave the way for the design of functional and stable neural interfaces, offering enhanced performance and versatility. This approach is crucial for creating highly adaptable devices that can seamlessly integrate into biological systems.

Device optimization. GO-based devices with mass transport characteristics in biological applications unfold a broad range of possible applications. These materials can modulate neural signals, record and stimulate neural activities, and offer long-term biocompatibility with minimal tissue reaction. 2D biomaterials thus hold significant promise in propelling the advancement of neuromorphic technologies and providing novel solutions to enhance the quality of life for individuals suffering from neurodegenerative diseases and neural injuries. Modifying GO-based devices by incorporating 2D structures into 3D architectures, such as scaffolds and microfluidic devices, could amplify their potential for large-scale and high-density neuromorphic applications. These include brain-computer interfaces, neuroprosthetics, and neurofeedback devices. Notably, the rapid progress in mimicking biological ion channels and constructing GO-based synaptic devices lends further confidence to these prospects.

Algorithm integration. GO-based neuromorphic devices are well-suited for event-driven neuromorphic computing and reservoir computing applications. Integration of these devices with Spiking Neural Networks and bioinspired learning algorithms to enhance real-time learning and inference capabilities would attract huge interest in future study. Furthermore, feedback-driven neuromorphic systems will leverage the unique properties of GO to improve adaptive learning and error correction in dynamic environments, making these devices ideal for adaptive neuroprosthetics and neurofeedback systems.

As fundamental research continues to unveil bio-inspired ion transport mechanisms in GO, and as device development addresses integration and energy-efficiency challenges, GO stands poised to bridge the gap between living neural systems and artificial neuromorphic computing in the years ahead.

Author Contributions

H.W.: writing—reviewing and editing; H.Z.: conceptualization, writing—original draft preparation, supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not applicable.

Conflicts of Interest

Given the role as Editor-in-Chief, Hongwei Zhu had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to polish the sentences in the paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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