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Resistive Switching, Device Optimization and Neuromorphic Applications of Gallium Oxide-Based Memristors

Jiyuan He

School of Electronic Engineering, Xidian University, Xi'an, China
24022100070@stu.xidian.edu.cn

Abstract. Gallium oxide-based memristors have attracted increasing attention for non-volatile memory, artificial synapses, and neuromorphic computing because of the ultra-wide bandgap, high resistance, chemical stability, and defect-tunable properties of Ga_2O_3/GaO_x. This paper reviews the material properties, typical device structures, resistive switching mechanisms, optimization strategies, and neuromorphic applications of gallium oxide-based memristors. The switching behavior is mainly related to oxygen-vacancy migration, conductive filament formation and rupture, metal-ion-assisted switching, and interface barrier modulation. Device performance is strongly influenced by oxide stoichiometry, electrode activity, film thickness, and interface quality. Approaches like defect adjustment, changes to the electrode and interface work, designing very thin or two-dimensional Ga_2O_3 structures can enhance switching stability, reduce the operating voltage, and improve analog conductance modulation. In neuromorphic applications, GaO_x-based memristors can emulate synaptic functions, such as emulating potentiation, depression, paired-pulse facilitation, and adjusting multilevel weights. Finally, the remaining challenges in endurance, uniformity, large-scale integration, and CMOS compatibility are discussed.

Keywords: GaO_x memristor, resistive switching, oxygen vacancy migration, conductive filament, neuromorphic computing

1. Introduction

The explosive growth of data-centric workloads, particularly in artificial intelligence, big data analytics, and the Internet of Things, has placed increasing demands on the speed and energy efficiency of conventional computing systems. However, in the traditional von Neumann architecture design, the physical separation of the central processing unit and memory creates the widely known "memory wall" issue, which leads to significant delays and increased energy consumption during frequent data transfer. Researchers have been looking for ways to fix these bottlenecks, and computing that happens inside memory has gotten new attention as a good way to make computation speed faster by cutting down on how often data must be moved back and forth outside the main processing parts [1].

To address this problem, memristors have gotten a lot of attention as a new kind of device for non-volatile memory, in-memory computing, and also neuromorphic hardware. In recent years, memristors that use gallium oxide have come up as promising options for making next-generation

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electronic devices, because this material possesses an ultra-wide bandgap, good thermodynamic stability, and excellent chemical resistance in Ga_2O_3.

In this field, new lab-based studies have proved that GaO_x-based memristors have real potential for use in neuromorphic systems. For instance, Ag/GaO_x/FTO devices exhibit multilevel storage capabilities, while Ga_2O_3-x-based RRAM devices enable synaptic weight modulation. Furthermore, Ti/GaO_x/W structures provide non-filamentary switching for highly reproducible analog states, and ultrathin Ga_2O_3 memristors can successfully emulate artificial synaptic functions.

Therefore, this review comprehensively discusses the material properties, resistive switching mechanisms, and key performance metrics of Ga_2O_3/GaO_x-based memristors, alongside essential optimization strategies and their potential applications in neuromorphic systems.

2. Material properties and device structures of gallium oxide-based memristors

2.1. Material properties of gallium oxide

Gallium oxide is an important ultra-wide-bandgap oxide semiconductor. Ga_2O_3 has several commonly reported polymorphs, including α-, β-, γ-, δ-, and ε-Ga_2O_3; among them, β-Ga_2O_3 is the stable form under normal conditions and has been the most widely studied and utilized. Owing to its large bandgap, Ga_2O_3 is particularly attractive for power electronics and solar-blind ultraviolet photodetectors [2]. In a 2026 study, Ghosh et al. from the Institute of Physics, Bhubaneswar, and the Homi Bhabha National Institute reported Ag/Ga_2O_3-x/p^{++}-Si resistive switching devices. Using radio-frequency magnetron sputtering, they investigated the effects of growth angle and film thickness, and reported direct and indirect optical bandgap values of 4.94 eV and 4.87 eV for the Ga_2O_3-x film, respectively [3].

For memristor applications, the wide bandgap of Ga_2O_3 provides a highly resistive oxide matrix in which oxygen vacancies can redistribute under an external electric field, leading to resistance modulation. Therefore, the switching behavior of Ga_2O_3/GaO_x-based memristors is closely related to defect chemistry, stoichiometry, film thickness, and interface conditions.

Sub-stoichiometric Ga_2O_3-x is particularly relevant for resistive switching. In Ag/Ga_2O_3-x/p^{++}-Si devices prepared by radio-frequency magnetron sputtering, growth angle and film thickness can tailor the resistive switching behavior: ≈15 nm films grown at an 80° glancing angle exhibit stable bipolar switching with an ON/OFF ratio of ≈10^5, whereas ≈30 nm films show threshold switching [3].

Amorphous $GaO_x$is also useful because it can be prepared by low-temperature thin-film processes and is suitable for large-area fabrication. In addition, ultrathin Ga_2O_3 structures can shorten ion migration paths and strengthen electrode/oxide interface effects, helping realize low-power and forming-free resistive switching.

2.2. Typical device structures

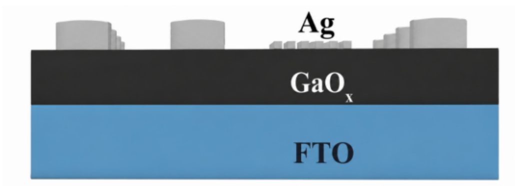

Figure 1. Schematic structure of the vertical Ag/GaO_x/FTO memristor

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Gallium oxide-based memristors usually adopt a vertical metal/oxide/electrode structure, where Ga_2O_3 or GaO_x serves as the resistive switching layer. One representative structure is Ag/GaO_x/FTO. As shown in Figure 1, the device adopts a vertical Ag/GaO_x/FTO configuration, with amorphous GaO_x as the resistive switching layer, Ag as the active top electrode, and FTO as the conductive bottom electrode. The device exhibited multilevel storage features, which include a retention time that is close to 10^4 s, endurance over 150 cycles, and more than 100 different conductance states, with a CNN recognition accuracy of 91.34% [4].

Beyond the basic active-electrode designs, changing the device interface and the thickness of the film gives other ways to make performance better. For example, adding asymmetric transport works really well: the W/WO_x/a-GaO_x contact acts as an ohmic contact, since the WO_x layer has many oxygen vacancies, while the a-GaO_x/ITO junction creates a Schottky junction that has asymmetric conductivity [5]. Ti/GaO_x/W structures also show how important interfacial effects are; they have non-filamentary, area-dependent switching. This process goes evenly across the whole device instead of only through localized filaments, so it makes the cycle-to-cycle reproducibility and analog modulation much better. Another option is that structures that use really thin Ga_2O_3 layers (like Pt/Ga_2O_3/n^+-Si) lower the defect migration distance a lot, which lets the device run well without needing a separate forming step at all.

2.3. Key performance metrics

The main performance metrics for gallium oxide memristors include SET/RESET voltage, ON/OFF ratio, retention time, endurance, and multilevel conductance states. During the SET process, the device changes from a high-resistance state to a low-resistance one, and the RESET process works the exact opposite way. Low and consistent SET/RESET voltages are essential to minimize power consumption and enhance device reliability. The ON/OFF ratio determines the distinguishability of memory states, and in comparison, retention and endurance show how stable the device is over a long time and the cycling reliability.

Table 1. Summary of representative Ga_2O_3/GaO_x memristors and key performance metrics

Device stack	Switching / key feature	Representative performance	Application / highlight	Ref.
Ag/GaO_x/FTO	Active-electrode bipolar switching; multilevel conductance modulation	Retention ~10^4 s; endurance >150 cycles; >100 conductance states	CNN handwritten-digit recognition accuracy 91.34%	[4]
Ag/Ga_2O_{3-x}/p^{++}-Si	Growth-angle and thickness tuned; bipolar or threshold switching	15 nm @ 80°: ON/OFF ~10^5; 30 nm film: threshold RS; retention up to ~10^3 s	Demonstrates the importance of growth-parameter engineering	[3]
W/WO_x/a-GaO_x/ITO	Ohmic W/WO_x/a-GaO_x contact and Schottky a-GaO_x/ITO junction	Asymmetric synaptic transport controlled by interface engineering	Representative interface-controlled GaO_x synaptic device	[5]
Ti/GaO_x/W	Non-filamentary, self-rectifying switching	1000 cycles; 12 potentiation states; 11 depression states	Highly repeatable analog states for artificial synapses	[6]
Pt/Ga_2O_3/n^+-Si	Ultrathin (~3 nm) 2D Ga_2O_3; forming-free bipolar switching	HRS/LRS ratio >100; retention >10^4 s	PPF, STDP, LTP/LTD synaptic plasticity	[7]

Notes: RS = resistive switching; PPF = paired-pulse facilitation; STDP = spike-timing-dependent plasticity; LTP = long-term potentiation; LTD = long-term depression. Data summarized from Refs [3-7].

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Multilevel conductance modulation is crucial for neuromorphic applications, since artificial synapses need gradual and controllable weight updates instead of just simple binary switching. The Ti/GaO_x/W device uses amorphous GaO_xthat was deposited by plasma-improved atomic layer deposition, and it shows non-filamentary switching, self-rectifying behavior, and resistance states that are very repeatable. It can be set to 12 different intermediate states when potentiation happens, and 11 different states during depression, which means it has good potential to make reproducible artificial synapses [6]. Ultrathin two-dimensional Ga_2O_3 memristors made with a squeeze-printing process also have forming-free bipolar switching, and they can copy different synaptic functions, like paired-pulse facilitation, spike-timing-dependent plasticity, long-term potentiation, and long-term depression [7].

Overall, Ga_2O_3/GaO_x memristor performance depends on four main things: defect chemistry, electrode activity, interface design, and device geometry. All the representative devices and their most important numbers are put together in Table 1.

3. Resistive switching mechanisms of gallium oxide-based memristors

3.1. Conductive filament formation and rupture

Conductive filament formation and rupture are widely used to explain oxide-based resistive switching [8]. Figure 2 schematically illustrates this process: conductive filaments are generated during the forming or SET process, leading to the low-resistance state, whereas partial filament rupture during RESET restores the high-resistance state.In Ga_2O_3/GaO_x-based memristors, the initial high-resistance state is closely related to the ultra-wide-bandgap nature of the oxide matrix. Under an applied bias, mobile species such as oxygen vacancies or metal cations can migrate and accumulate locally, gradually forming conductive paths. Furthermore, non-stoichiometric GaO_x films inherently contain oxygen-vacancy-rich regions, and these regions can work as better nucleation places for filament growth. These defect-rich regions facilitate filament formation, reduce the required forming voltage, and stabilize the switching path.

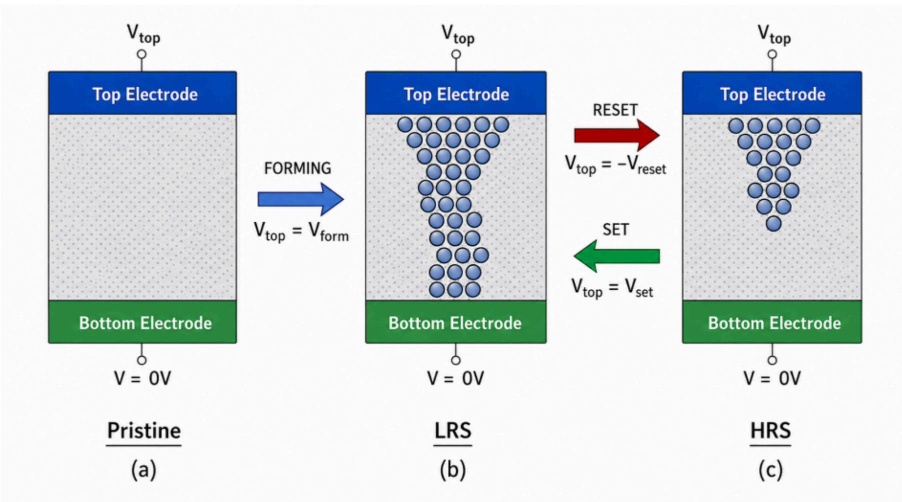

Figure 2. Schematic illustration of conductive filament formation and rupture in oxide-based resistive switching memory

Filaments made of oxygen vacancies are usually connected to the valence change mechanism: oxygen ions move around under an electric field and leave oxygen vacancies behind, which

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increases the local carrier concentration and forms a low-resistance path. When active electrodes such as Ag are used, metallic filaments can also form through electrochemical processes.

The conductive filament mechanism can also be investigated through current-voltage fitting. When the system is in the LRS state, the current closely follows ohmic conduction, which shows that charge carriers move through a path that is fully connected. When the system is in HRS, how carriers move can be controlled by trap states and the interface barriers. Common examples of this kind of control include space-charge-limited conduction, Poole – Frenkel emission, Schottky emission, trap-assisted tunneling, or hopping conduction.

3.2. Oxygen vacancy migration

Oxygen vacancy movement is one key working mechanism found in memristors that are based on Ga_2O_3/GaO_x. Unlike just a standard general oxide-switching process, how vacancies move in gallium oxide gets strong influences from the material's crystal structure, its defect chemistry, and how much structural disorder it has. For crystalline β-Ga_2O_3, the monoclinic lattice can cause oxygen-vacancy movement that depends on direction, which makes how defects rearrange themselves sensitive to crystallographic orientation. In amorphous GaO_x, the disordered atomic network can provide spatially distributed migration paths, letting oxygen-related defects rearrange themselves in a more continuous way when an electric field is applied.

This difference matters a lot for how memristors work, because when vacancies build up in one small spot, it can support sudden filamentary switching, while a more even spread of oxygen rearrangement can create slow, gradual changes in conductance. In amorphous GaO_x systems, Aoki et al. attributed such non-filamentary memristive behavior to bulk mixed ion–electron conduction (MIEC) [9]. In this mechanism, the applied voltage changes how oxygen-related defects spread throughout the film, rather than forming a single narrow conductive bridge between the electrodes. The resulting I–V hysteresis comes from the combined drift and diffusion of mobile ionic defects and electronic carriers, leading to a spatially distributed change in conductance.

3.3. Metal ion-assisted switching

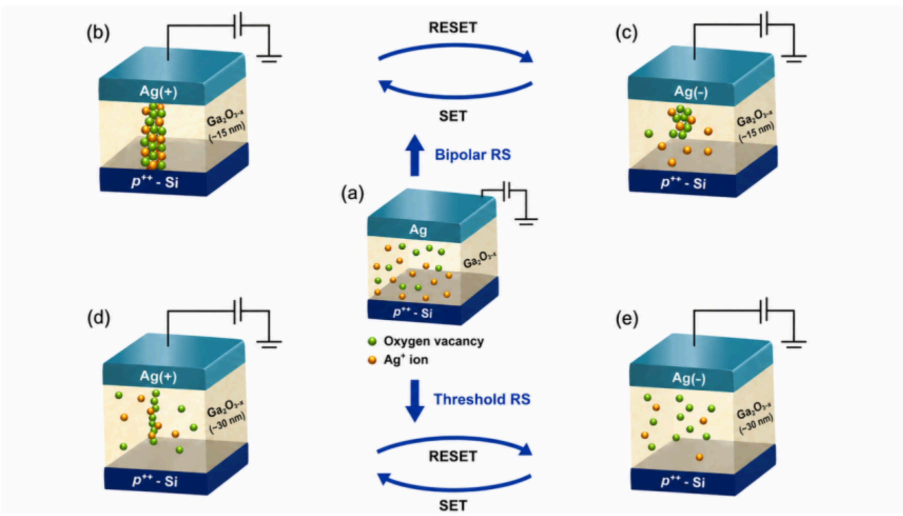

Figure 3. Physical model of resistive switching in an $Ag/Ga_2O_{3-x}/p^{++}$-Si memristor. The switching process is associated with Ag^+ ion migration, oxygen vacancy redistribution, and conductive filament formation or rupture under different bias polarities and film thicknesses

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When active electrodes such as Ag or Cu are used, metal-ion-assisted mechanisms may also contribute to the switching process. Under a positive bias applied to the Ag electrode, Ag atoms turn into Ag^+ ions through oxidation. These ions then migrate through the oxide layer, and are reduced back to metal near the counter electrode, or sometimes inside the film itself. The metal conductive bridge that forms this way, combined with changes in how oxygen vacancies are spread out, helps push the SET process along. Under reverse bias, the metallic filament dissolves or ruptures, corresponding to the RESET process and recovery of the high-resistance state. As shown in Figure 3, Ag^+ migration and oxygen vacancy redistribution jointly determine the resistive switching behavior in $Ag/Ga_2O_{3-}x/p^{++}$-Si devices. The figure further shows that the switching mode depends on film thickness: ≈15 nm $Ga_2O_{3-}x$ favors bipolar resistive switching, whereas ≈30 nm $Ga_2O_{3-}x$ is associated with threshold switching.

For Ag/GaO_x or Ag/Ga_2O_3 structures, Ag^+ ions promote metallic bridge formation, while oxygen vacancies modify local conductivity and trap distribution. Their coupled effect can reduce the energy barrier for conductive path formation. However, metallic filament growth is often stochastic, which may lead to cycle-to-cycle and device-to-device variations. Metal-ion-assisted switching is also related to multistate resistance behavior, because the number, size, and connectivity of metallic filaments can determine the final resistance state [10].

Basically, the switching behaviors in Ga_2O_3/GaO_x memristors come from a complex mix of oxygen defect movement, metal ion migration, and interface effects. Consequently, this variety means people need targeted optimization—like managing defects, picking the right electrodes, and adjusting the interface—to get reliable electrical characteristics.

4. Optimization strategies for gallium oxide-based memristors

4.1. Defect and oxygen vacancy modulation

Defect and oxygen vacancy modulation is a fundamental strategy for optimizing Ga_2O_3/GaO_x-based memristors. Oxygen vacancies provide the physical basis for resistance modulation, but their concentration must be carefully controlled. Too few vacancies may lead to high forming voltage or weak switching, whereas excessive vacancies may increase leakage current, reduce the HRS/LRS window, and even cause irreversible breakdown.

Vacancy concentration can be adjusted by deposition conditions, film stoichiometry, oxygen partial pressure, sputtering power, and post-annealing treatment. Oxygen-deficient GaO_x films tend to show stronger switching because pre-existing vacancies assist conductive path formation. For neuromorphic applications, however, defect modulation should not only form a stable low-resistance path, but also provide continuously tunable conductance states. Distributed defects and partially connected paths are more suitable for analog weight updates than a single thick filament.

In practice, defect modulation can be evaluated by SET/RESET voltage distribution, resistance-state stability, endurance, and I–V fitting. Trap-related HRS conduction indicates the role of defects, while ohmic LRS conduction usually suggests the formation of conductive paths.

4.2. Electrode and interface engineering

Electrode and interface engineering is another important method for improving Ga_2O_3/GaO_x memristors. The electrode/oxide interface affects carrier injection, ion migration, oxygen-vacancy accumulation, and filament nucleation. Active electrode materials, like Ag, can release mobile metal ions, and they help electrochemical filaments form more easily. This ultimately reduces the SET

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voltage. Chemically inert electrodes like Pt and Au, on the other hand, mostly work with switching that is mediated by oxygen vacancies, and also help change Schottky barriers. But W counts as a semi-active electrode; this is because it can form a WO_x interfacial layer when oxygen is present or when there is an electrical bias. This layer of WO_x works like a storage space for oxygen vacancies, it cuts down on leakage current, and also takes part in redox reactions that happen at the interface. All of this leads to a mixed kind of switching behavior.

Adding an extra interfacial layer between materials can help adjust vacancy distribution and the way carriers get injected even better. To give an example, in the Au/β-Ga_2O_3/WO_3/Ag bilayer memristor, the WO_3 adds one more oxide interface, and it can work as a region that has lots of oxygen vacancies. This two-layer structure makes a region with a defect gradient, which makes it easier to control how filaments form and break apart [11].

The Au/β-Ga_2O_3/WO_3/Ag device that was reported shows two-way resistive switching behavior, has a resistance ratio of around 182, can keep working for 300 switching cycles, and keeps its memory effect for 10^3 seconds. These results show that engineering the bilayer interface can make switching more stable and cut down on how much device performance varies from one unit to another.

4.3. Ultrathin and two-dimensional Ga_2O_3 structure design

Ultrathin two-dimensional Ga_2O_3 structures offer one more way to improve device performance. Compared with conventional thick films, these ultrathin switching layers reduce the migration distance of oxygen vacancies, oxygen ions and metal ions. This helps lower both the forming voltage and the operating voltage that the device needs. At the same time, these structures have a much bigger ratio of interface to volume, and this makes the electrode/oxide interface effects stronger. This facilitates low-power operation and enhances analog conductance modulation.

Because Ga_2O_3 is not a typical layered van der Waals material, large-area monolayer or few-layer Ga_2O_3 is difficult to obtain by mechanical exfoliation. Liquid-metal-based methods offer an alternative. Gallium can naturally form a self-limiting Ga_2O_3 skin in air, which can be transferred or printed onto substrates.

Quasi-two-dimensional β-Ga_2O_3 films fabricated from room-temperature liquid metal oxide skin also show the feasibility of scalable Ga_2O_3 integration [12]. For memristor applications, ultrathin Ga_2O_3 can reduce switching voltage, enhance interface control, and support flexible or large-area neuromorphic hardware. Even so, problems still exist, like uneven thickness, leftover metallic gallium, and unwanted leakage current. Work done in the future will need to make improvements to printing, transfer steps, interface cleaning, and also post-treatment processes.

In summary, defect adjustment decides how usable and stable switching paths are. Interface design manages ion movement and how carriers get injected. And when the device is made with an extremely thin structure, this cuts down migration distance and makes interface effects stronger. Combining these strategies is expected to improve the stability, power consumption, and neuromorphic functionality of gallium oxide-based memristors.

5. Performance comparison and neuromorphic functionality

5.1. Performance comparison with other memristor systems

Based on the discussion in the previous chapters, Ga_2O_3/GaO_x-based memristors show promising potential for neuromorphic computing because of their high material stability, simple device

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configuration, oxygen-vacancy-mediated resistance modulation, and multilevel conductance tunability. For memory applications, SET/RESET voltage, ON/OFF ratio, retention, and endurance are important evaluation metrics. For neuromorphic applications, however, gradual conductance modulation, repeatability, linearity, symmetry, and device-to-device uniformity are more critical because they directly affect synaptic weight updating and neural network performance.

Compared with other recently reported neuromorphic memristors that are listed in Table 2, GaO_x-based devices exhibit superior material stability, simple device structure, and multilevel conductance modulation. For example, while Ag/GaO_x/FTO devices can get stable bipolar switching, multilevel storage, and synaptic-like conductance adjustment to work properly, their endurance and large-scale uniformity require further improvement. By comparison, $Ti_3C_2T_x$ MXene thin-film memristors have a switching speed as fast as 30 ns, an ON/OFF ratio of around 10^3, can keep working after more than 500 cycles, and can hold memory information for 10^4 seconds. This result shows that high-quality two-dimensional film engineering serves as a crucial design reference for enhancing the switching speed and array-level reliability of GaO_x devices [13].

Table 2. Comparative design implications of different neuromorphic memristor systems. Note: MOF = metal-organic framework; COF = covalent organic framework; HOF = hydrogen-bonded organic framework

Memristor system	Main material / structural characteristic	Neuromorphic advantage	Main limitation	Design implication for Ga_2O_3/GaO_x memristors
Ga_2O_3/GaO_x-based memristors	Ultra-wide-bandgap oxide matrix with oxygen-vacancy, metal-ion, and interface-related resistance modulation	Good material stability, simple vertical structure, and multilevel conductance modulation	Endurance, cycle-to-cycle fluctuation, and device-to-device uniformity still require improvement	Precise defect control, stable interface design, and electrode engineering are needed to improve analog weight modulation
MXene thin-film memristors	Two-dimensional $Ti_3C_2T_x$-based thin films with surface-termination-related properties	Fast switching and potential for flexible or large-area neuromorphic devices	Oxidation stability and film-quality control remain important issues	Two-dimensional film engineering provides a useful reference for improving GaO_x film uniformity and array-level reliability
Organic-framework-based memristors	MOF / COF / HOF materials with tunable active sites, pores, and charge transport pathways	Highly tunable structure and ion/trap-related switching behavior	Long-term stability, reproducibility, and integration still need improvement	Active-site and trap-state regulation can inspire more controllable defect engineering in GaO_x devices

5.2. Artificial synaptic behavior

In GaO_x memristors, synaptic behavior is driven by the movement of Ag ions and oxygen vacancies. Positive pulses cause Ag^+ drift and localized oxygen vacancy accumulation, gradually increasing conductance to emulate long-term potentiation (LTP). Conversely, negative pulses rupture the conductive filament, decreasing conductance to emulate long-term depression (LTD).

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Short-term plasticity, which is usually called STP, happens when the movement of ions or the forming of new filaments is not fully finished. One common example is paired-pulse facilitation, also known as PPF, where the second pulse of electricity gives a much stronger current response than the first one. This occurs because active ions and structural defects persist after the initial pulse. When the gap of time between two pulses gets longer and longer, these leftover effects slowly disappear, resulting in a decrease in the facilitation index.

For GaO_x devices, changing the pulse settings gives a straightforward method to control different kinds of synaptic functions. Lower voltage levels normally lead to temporary changes in the device's conductance, which works just like short-term memory. When pulses are stronger or come more than once, they help build more solid conductive paths, and this pushes the device to switch into a long-term memory state. By just making simple adjustments to these electrical parameters, GaO_x memristors can recreate STP, LTP, and LTD, and they also allow multi-level control over the weights of the synapses.

5.3. Neural network and image recognition applications

The main final goal of artificial synaptic memristors is to make hardware that can run neural networks in an efficient way. In a crossbar array that's built from memristors, the conductance of every single device can stand for the weight of a synapse. When input voltages are applied to the array, the output current can do the matrix-vector multiplication step directly, which works according to Ohm's law and also Kirchhoff's current law. As Figure 4 shows, pairs of memristive devices can store both positive and negative conductance values for convolutional kernels. At the same time, peripheral circuits, subtractors, and analog-to-digital converters get used to handle the outputs coming from the array, all to make hardware neural network computing work properly.

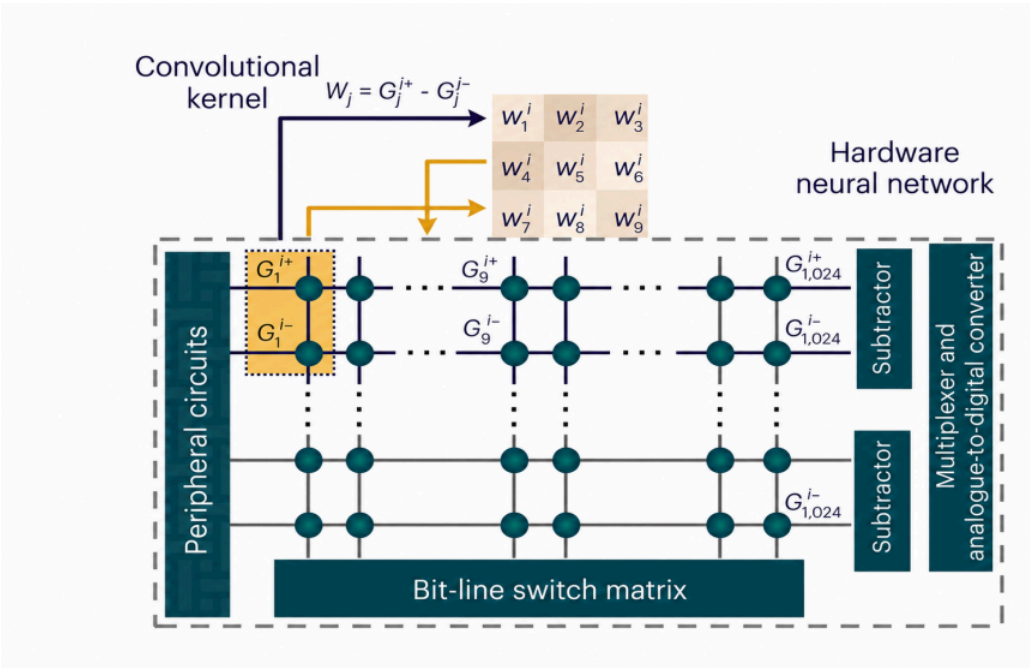

Figure 4. Schematic illustration of a memristive synaptic crossbar array for hardware neural network computing

For hardware-based image recognition, analog conductance states are crucial for precise synaptic weight mapping. GaO_x-based memristors have already demonstrated this capability; for instance, Ag/GaO_x/FTO devices exhibit multilevel conductance modulation suitable for CNN-based handwritten digit recognition. To further enhance weight mapping precision, memristors utilizing van der Waals metallic cathodes (such as graphene or $PtTe_2$) offer a valuable design reference. By regulating Ag ion intercalation, these devices achieve a massive resistance window (ON/OFF ratio up to 10^8) simultaneously with highly stable >8-bit analog states [14].

Translating these device-level advancements into practical neural networks will ultimately depend on maintaining this high-resolution analog behavior uniformly across large-scale crossbar arrays.

6. Conclusion

This review systematically explores how gallium oxide memristors operate, how they can be improved, and what potential they have for neuromorphic computing. Ga_2O_3/GaO_x has an ultra-wide bandgap, high natural resistance, stays stable chemically, and responds strongly to changes in oxygen vacancies, making it a highly suitable foundation for non-volatile memory and brain-inspired hardware.

Fundamentally, resistive switching is typically governed by three primary mechanisms: oxygen vacancies moving around, changes in filament dynamics, or shifts in the interfacial energy barrier. In the end, how the device behaves — whether it has sharp binary switching or smooth analog modulation — depends on the balance between limited filamentary conduction and more spread out defect diffusion.

To harness these mechanisms, targeted structural optimization is essential. Carefully modifying the defect profile can directly change the forming voltage, resistance window, and retention stability. Refined interface and electrode engineering helps control ion injection and filament nucleation, which makes the uniformity much better. Furthermore, using ultrathin or two-dimensional Ga_2O_3 structures cuts down the distance ions have to travel and makes interfacial effects stronger. This structural design opens the door for ultra-low-power operation that doesn't need a forming step.

In practical applications, GaO_x devices can effectively emulate biological synaptic functions. Owing to their continuously tunable conductance, they enable direct weight mapping in hardware neural networks, and also handle image recognition tasks. Despite this potential, practical deployment still faces several hurdles. These challenges primarily involve long-term endurance degradation, cycle-to-cycle and device-to-device variability, large-scale array integration, and compatibility with existing CMOS technology. If these integration problems can be fixed, Ga_2O_3/GaO_x memristors will become a core base building block for the next generation of neuromorphic computing.

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