

Nanoions tuned two-dimensional van der Waals materials for information devices

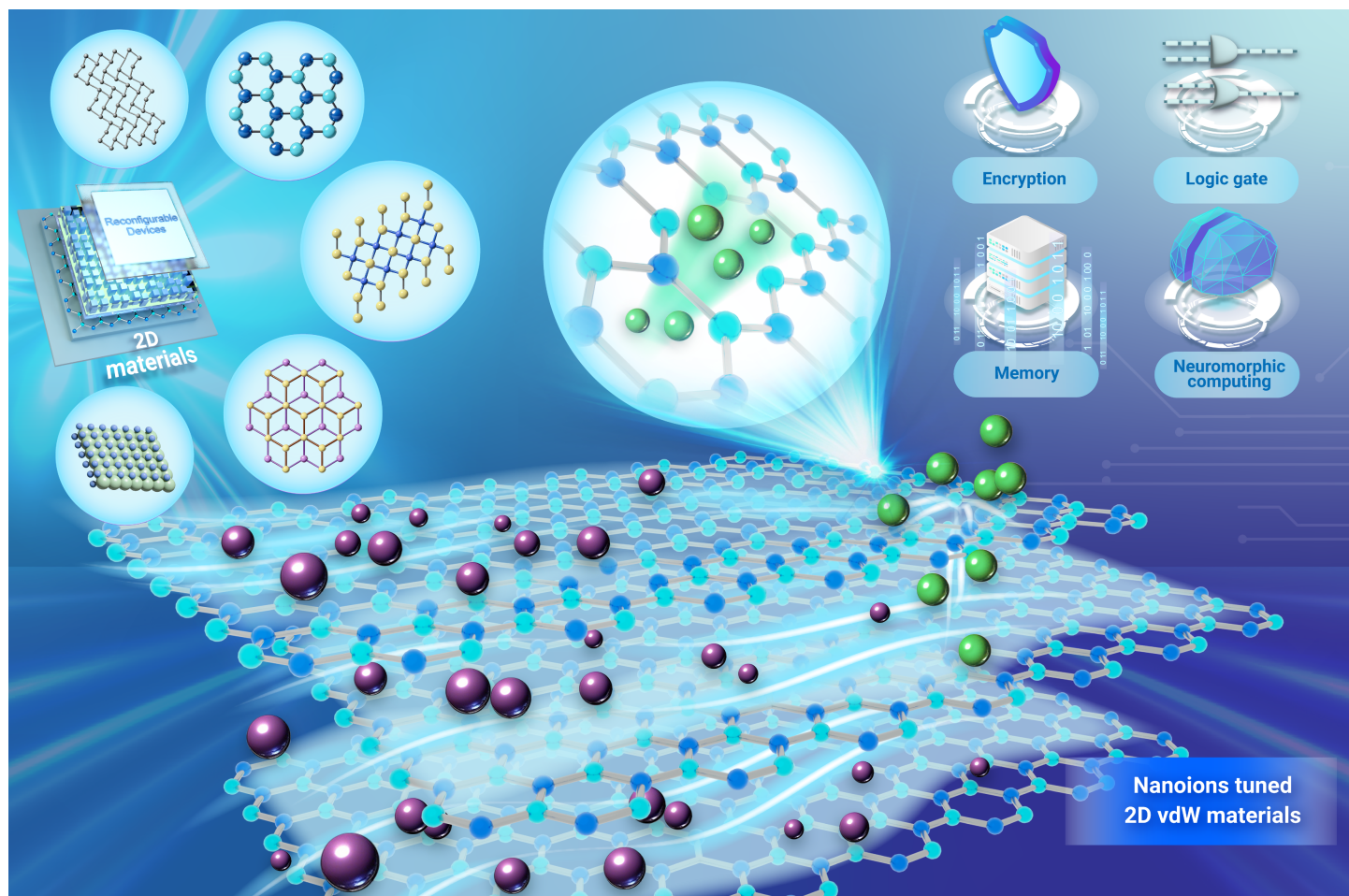
Yanyu Zhang,^{1,2,3} Xiaojian Zhu,^{1,2,3,*} Runsheng Gao,^{1,2,3,*} Ziyi Zhang,^{1,2,3} and Run-Wei Li^{1,4,*}

*Correspondence: zhuxj@nimte.ac.cn (X.Z.); rsgao@nimte.ac.cn (R.G.); rwli@eitech.edu.cn (R.L.)

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Nanoionics in two-dimensional (2D) materials and its impact on electrical properties are summarized.
- Ion-driven 2D materials-based reconfigurable devices for information technology are discussed.
- Opportunities for developing reconfigurable devices and expanding their multifunctionality are presented.

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Yanyu Zhang,^{1,2,3} Xiaojian Zhu,^{1,2,3,*} Runsheng Gao,^{1,2,3,*} Ziyi Zhang,^{1,2,3} and Run-Wei Li^{1,4,*}

¹Ningbo Institute of Materials Technology & Engineering, CAS, Ningbo 315201, China

²Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

³University of Chinese Academy of Sciences, Beijing 100049, China

⁴Ningbo Institute of Digital Twin, Eastern Institute of Technology Ningbo, Ningbo 315200, China

*Correspondence: zhuxj@nimte.ac.cn (X.Z.); rsgao@nimte.ac.cn (R.G.); rwli@eitech.edu.cn (R.L.)

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The rapid advancement of artificial intelligence (AI) and the Internet of Things (IoT) has triggered an escalating demand for high-performance, miniaturized, and multifunctional electronic information devices. Silicon-based electronics, which have laid the foundation for the electronics industry over the past few decades, are now approaching the physical limitations with the extension of Moore's law. Two-dimensional (2D) van der Waals (vdW) materials have emerged as promising candidates for next-generation electronic devices, due to their atomic-scale thickness, wide range of material choices, and excellent physical property tunability. Notably, it has been demonstrated that 2D vdW materials can facilitate ion migration under an electric field, enabling the reversible and efficient modulation of electrical resistance. Such a characteristic unlocks new possibilities for the design and construction of multifunctional and reconfigurable information devices. This review delves into the generation and transport of nanoions in 2D vdW materials and their impact on modifying electrical properties. It explores strategies for device architecture design and their applications in advanced information processing. The latest progress in ion-driven reconfigurable devices for memory, logic-in-memory, neuromorphic computing, and data encryption is systematically summarized. Challenges in this field and future research directions are also discussed.

INTRODUCTION

Over the past few decades, silicon-based materials have played a pivotal role in advancing semiconductor technology, significantly boosting the performance of electronic devices and profoundly shaping modern life.^{1–3} These achievements have primarily relied on the continuous downscaling of metal-oxide-semiconductor field-effect transistors (MOSFETs).^{4–7} In recent years, the rapid emergence of information technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), has led to increasingly stringent demands on data processing capabilities.^{8–10} To meet the performance requirements of next-generation electronics, numerous efforts have been devoted to enhancing functionality and system integration.^{11–13} Among various strategies, reconfigurable devices have gained attention for their ability to consolidate multiple device functionalities into a single unit.^{14–16} This approach enables flexible adaptation to diverse application scenarios, reduces system complexity, and supports further miniaturization. While conventional silicon-based reconfigurable devices offer relatively stable performance and have reached a certain level of maturity, scaling challenges like electron drift and leakage current persist.^{17,18} Moreover, silicon-based integrated circuit technology is approaching its physical limits in the sub-10 nm regime, as structural limitations and reliance on auxiliary peripheral circuitry hinder further miniaturization.^{19,20} Therefore, it will be of great significance in investigating novel materials and reconfigurable intelligent devices for the next generation of information processing technologies.

Two-dimensional (2D) van der Waals (vdW) materials are atomic-scale layered materials with either a single or a few layers of atoms arranged in a planar lattice. Saturated covalent bonds connect the atoms in the layer, and vdW interactions occur across layers. Inspired by graphene, researchers have explored various classes of other 2D vdW materials, and the majority of them derive from Group III–VI elements (such as B, C, N, and S) and their compounds, along with transition metals (such as Ti, Mo, and W) in layered structures like metal carbides or nitrides (MXenes) or transition metal

dichalcogenides (TMDs).^{21,22} These materials range from conductors (such as graphene) to semiconductors (such as MoS₂) and insulators (such as h-BN), offering distinct electrical and optical properties.^{23,24} Their layered structure confines electron transport perpendicular to the 2D plane, with quantum confinement effect shaping their band structure.^{25–28} In addition, owing to the inert surface free of dangling bonds, the interface of 2D vdW materials is nearly defect-free.^{29–31} This high-quality interface significantly reduces charge scattering, enabling high charge carrier mobility.^{32–35} Consequently, materials such as MoS₂,^{36,37} WS₂,³⁸ WSe₂,³⁹ MoTe₂,⁴⁰ and h-BN,⁴¹ have demonstrated excellent electronic performance in ultra-short gate length and ultra-thin channel field-effect transistors (FETs),^{42–44} significantly reducing energy consumption by mitigating short-channel effects and optimizing efficiency.^{45–48} Although the excellent electronic performance has enabled 2D materials to achieve remarkable success in electronic devices,^{49–51} further strategies are needed to enhance the functionality of 2D material-based electronic devices for energy-efficient miniaturization.

Recently, reconfigurable nanoionic devices based on 2D vdW materials have garnered widespread attention in the field of information technology.^{52–55} The layered structure of 2D vdW materials leads to highly anisotropic ion transport, whereby ions migrate either within the vdW gap or across layers under the influence of electric fields.^{56–59} Controlled ion migration within these materials enables reversible modulation of local electronic states, allowing devices to switch between distinct functional states.^{60,61} This ion-driven reconfigurability facilitates tunable electrical responses, such as adjustable resistance, memristive behavior, and phase transitions, thereby significantly enhancing device multifunctionality.^{62–65} Additionally, defects within 2D materials, such as vacancies and grain boundaries, can be intentionally engineered to optimize ion migration pathways.^{66–68} These defects provide more precise control over ion transport dynamics and spatial distribution, enabling the design of devices with rapid switching speeds (120 ps),⁶⁹ robust retention (10⁵ s),⁷⁰ excellent endurance (10⁷ cycles),⁷⁰ and low energy consumption (8.8 zJ).⁷¹ These capabilities open new avenues for compact, multifunctional reconfigurable electronic devices. Therefore, a detailed understanding of the dynamic behavior of ions in 2D vdW materials and their impact on device operation is crucial for advancing next-generation intelligent information devices.

Here, we present a review of the advancements in ion-driven 2D materials-based novel electronic devices, aiming to facilitate the development of miniaturized, multifunctional, and reconfigurable electronic devices (Figure 1). The mechanisms of ion migration in 2D materials have been thoroughly analyzed, and their impact on reversibly modulating the electrical properties of 2D materials, including phase structure, band structure, and interfacial barriers, has been discussed. The dynamic and non-destructive modulation, along with precise control over the resistance of 2D materials, was achieved through electric field-driven nanoionics, which possess outstanding reconfigurable electrical performance. The design strategies of device architecture were further summarized to enable diverse resistance states and advanced information processing. In addition, recent advancements in ion-driven 2D materials-based reconfigurable devices across various areas were outlined, including high-density storage, in-memory computing, data encryption, and sensing. Finally, the current challenges and potential innovation directions of reconfigurable electronic devices are highlighted, providing an important guidance for the development of future intelligent devices.

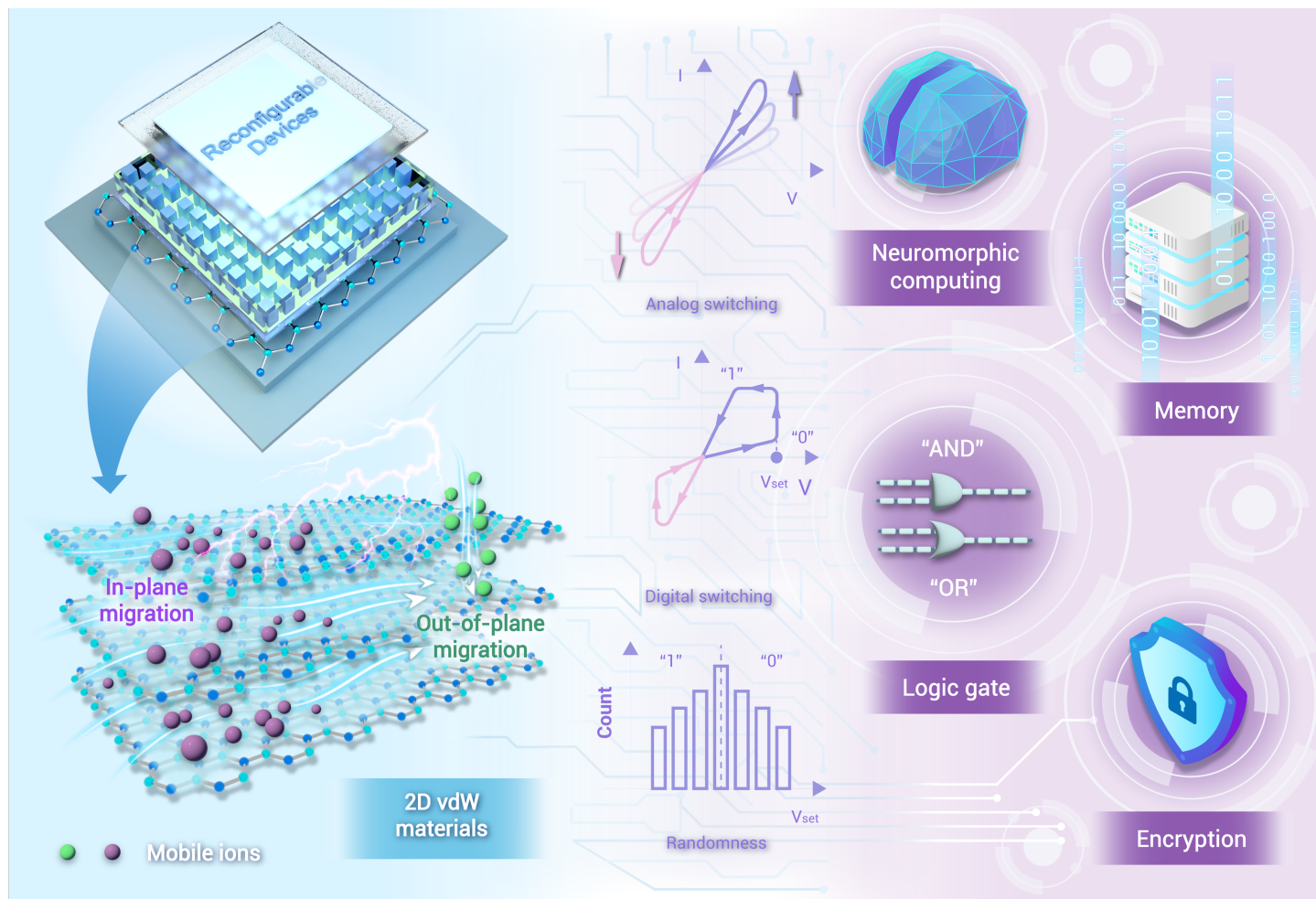


Figure 1. Schematic diagram of ion migration within 2D vdW materials-based devices, diverse electrical characteristics of these devices, and their applications for information processing The left panel: A device prototype based on 2D vdW materials involving ion migration. The middle panel: Distinct electrical characteristics of ion-driven reconfigurable devices fabricated from 2D vdW materials, including digital and analog switching. Digital switching refers to abrupt, discontinuous resistive switching behavior, where the device's resistance changes sharply and dramatically. Analog switching refers to gradual, continuous resistive switching behavior without abrupt current jumps. The right panel: Diverse functional applications leveraging these devices, including neuromorphic computing, memory storage, logic computing, and encryption.

ION MIGRATION IN 2D VDW MATERIALS

2D vdW materials have atomic-scale thickness and ultra-high specific surface area, distinguishing them significantly from conventional bulk materials. They have been studied in fields such as energy storage, catalysis, and sensors, demonstrating vast potential for future applications.⁷²⁻⁷⁵ Ion migration plays a crucial role in governing the physical and chemical properties of 2D vdW materials, directly affecting the crystal structure, band structure, carrier concentration, interface transport efficiency, and reconfigurability of 2D materials.^{56,76,77} The abundant modulation methods of ion migration have injected new vitality into the development of next-generation reconfigurable devices.

Origin of mobile ions

Mobile ions within 2D materials can be categorized into two main types based on their origin: intrinsic and extrinsic. The migration of these ions plays a crucial role in determining the electrical, optical, and chemical properties of 2D materials.^{53,78} Intrinsic ions originate from the 2D materials and contribute to the characteristics and stability of the material. Extrinsic ions are externally introduced via processes such as electrochemical ion injection and ion intercalation. Under an applied electric field, both types of ions migrate within the 2D lattice. Thus, understanding their origins is essential for enhancing the stability and functionality of 2D materials.

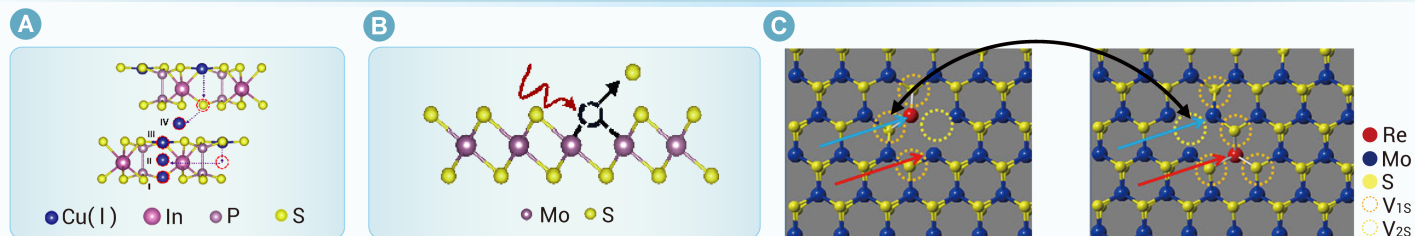
Intrinsic ions. Intrinsic ions in 2D vdW materials arise from ionization, where atoms in the lattice gain or lose electrons due to structural defects or external stimuli, forming charged vacancies and interstitials that significantly influence material physical properties.⁷⁹⁻⁸² A representative example is the Cu⁺

ions in the 2D monoclinic CuInP₂S₆. The crystal structure of CuInP₂S₆ consists of a sulfur framework, with metal cations (Cu and In) and P–P pairs occupying the octahedral voids.⁸³ The unstable Cu⁺ ions can occupy three crystallographic sites: (1) intralayer position shifted from the centers of the octahedra (position I and III), (2) interstitial position at the centers of the octahedra (position II), and (3) interlayer position located in the vdW gap (position IV) (Figure 2A). Under an external electric field, Cu⁺ ions migrate among lattice sites, vacancies, interstitial and interlayer positions, creating multiple potential wells states.⁸⁴ This dynamic migration has been directly observed via aberration-corrected scanning transmission electron microscopy,⁸⁵ providing critical insights into intrinsic ion migration in 2D materials and guiding the design of nanoionics-driven devices.

Moreover, intrinsic ions can be created through the formation of vacancies triggered by external excitation such as mechanical strain, irradiation, and electric fields.⁸⁶⁻⁸⁸ When an atom acquires sufficient energy to overcome the vacancy formation barrier, it breaks covalent bonds, escapes from its original lattice site, and becomes an ion, creating a charged vacancy (Figure 2B). This charged vacancy can migrate under an electric field, as exemplified by sulfur vacancies in MoS₂ and WS₂, boron vacancies in h-BN, and copper vacancies in Cu₂S.⁸⁹⁻⁹¹ Notably, vacancy migration is commonly accompanied by ion migration, as surrounding ions may hop into nearby vacancies, generating a new vacancy at the original site (Figure 2C).⁹² As these ions and vacancies shift, they create paths for charge carriers. This coupled migration behavior facilitates continuous ion transport within the 2D lattice and plays a critical role in modulating the electrical and ionic conductivity of 2D materials.⁹³

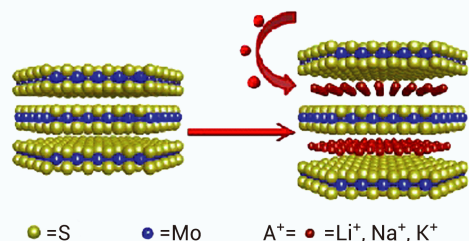
Extrinsic ions. Extrinsic ions in 2D vdW materials primarily originate from

Intrinsic ions



Extrinsic ions

D Ion intercalation



E Electrochemical reaction

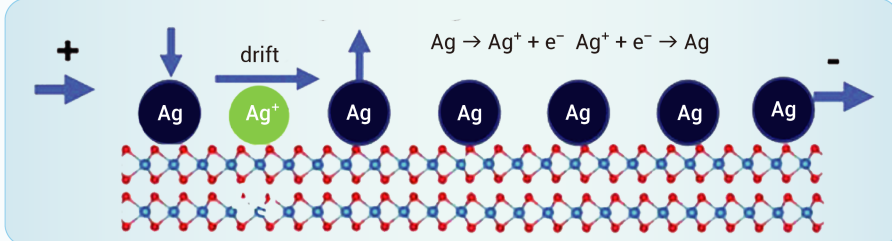


Figure 2. Schematic representation of the categories of mobile ions in 2D materials (A–B) Intrinsic ions in 2D materials, including (A) interstitial ions and (B) charged vacancies, as well as free ions formed by lattice atoms that have escaped from their original positions. Adapted with permission.⁸⁵ Copyright 2024, Springer Nature. (C) Vacancy-assisted ion migration processes in 2D materials. Adapted with permission.⁹² Copyright 2019, American Physical Society. (D–E) Schematic of extrinsic ions introduced into 2D materials via (D) ion intercalation and ion (E) electrochemical redox reaction. Adapted with permission.⁹⁴ Copyright 2014, Springer Nature. Adapted with permission.¹⁰⁷ Copyright 2019, Wiley-VCH.

heteroatoms introduced during synthesis or processing, as well as ions incorporated through ion intercalation and electrochemical redox reactions. Ion intercalation enables the reversible insertion of metal cations, such as Li⁺, Na⁺, and K⁺ ions, dissolved in a solvent into the vdW gap (Figure 2D),⁹⁴ thereby enhancing the functionality of 2D materials.^{95,96} For example, Li⁺ ions can be introduced into MoS₂ using a reagent such as butyllithium.⁹⁷ The corresponding lithiation reaction is as follows:



During the reaction process, Li⁺ ions migrate into the interlayer of MoS₂, and the insertion is fully reversible when x is in the range of $0 \leq x \leq 1$.⁹⁸ Furthermore, many studies have demonstrated that defects in 2D materials facilitate the migration of intercalated ions. For instance, the result of the first-principles calculation showed that the creation of sulfur vacancies effectively reduce the energy barrier for the insertion of K⁺ ions into the interlayer of WS₂.⁹⁹ Luo et al. reported that the interlayer defects serve as active sites that can absorb more Na⁺ ions, it will significantly reduce the diffusion barrier for Na⁺ ion migration in WS₂.¹⁰⁰ These intercalated ions have profound effects on 2D materials, such as doping, enhancing energy storage capabilities, and inducing phase transitions.^{101–103}

In addition, when 2D materials are in contact with active metal atoms (e.g., Ag, Cu), electrochemical redox reactions enable the introduction of metal cations generated by the electrode into the 2D material.^{78,104–106} This process typically requires an external electric field to drive the following reaction:



where M represents the metal atoms such as Ag, Cu, Ti, and Ni, and M^{n+} represents the corresponding metal cations such as Ag⁺, Cu²⁺, Ti²⁺, and Ni²⁺ ions (Figure 2E).¹⁰⁷ Many studies have shown that the migration of these external metal ions into 2D materials often leads to the formation of conductive filaments or clusters, which is the driving force behind the operation of conductive bridge random access memory.^{108,109}

Mechanisms of ion migration. 2D materials provide a confined, anisotropic environment for ion migration, where ions are constrained within an atomically thin interlayer.¹¹⁰ Ion migration is determined not only by

conventional driving forces such as concentration gradients (thermal-driven stochastic migration from high-concentration to low-concentration regions) and electric fields (directional migration under the net electrostatic force),^{111–113} but also by the intrinsic structure of 2D lattices, including layer stacking order, interlayer spacing, and defects.¹¹⁴ These factors create a highly heterogeneous energy landscape with direction-dependent migration pathways and energy barriers, which significantly influence ion migration dynamics.

Ion migration involves both diffusion and drift, which rely on the hopping of ions from one location to another. In 2D vdW materials, ions migrate through the specific energy landscape of potential wells, which provide localized states for ion trapping (Figure 3A).¹⁰⁷ In the absence of electric fields, ion diffusion exhibits pronounced anisotropy due to significant variations in diffusion energy barriers U_a along different crystallographic directions, which arise from the different atomic bonding and lattice symmetry within the 2D plane and between layers.^{115–118} Consequently, the ion diffusion rates are strongly governed by the migration direction, as illustrated dramatically by the room-temperature diffusion of Na⁺ in borophene, which is 8.1×10^4 times faster along the zigzag direction than along the armchair direction.¹¹⁹ Additionally, under an applied electric field, the energy barrier for ion hopping along the field direction is effectively reduced by a factor of aqV , where q , V , and a are the elementary charge, potential difference, and a constant, respectively. For instance, the migration barrier of Ag⁺ ions on the MoS₂ surface is lowered by $qVd/2$ under an electric field, where d is the migration distance.¹⁰⁷ Due to the exponential dependence of ion migration on the barrier, it is significantly enhanced along the electric field direction, resulting in directional ion drift predominantly along specific in-plane or interlayer pathways.

For ions migrating in 2D materials with an electric field strength of E , the dynamic evolution of the ion migration can be quantitatively described by the drift-diffusion continuity equation:

$$\partial n_d / \partial t = \nabla \cdot (D \nabla n_d - \mu E n_d) \quad (3)$$

Here, the ion diffusivity D is temperature-activated through the Arrhenius equation:

$$D = D_0 \exp(-U_a/kT) \quad (4)$$

Mechanism of ion migration

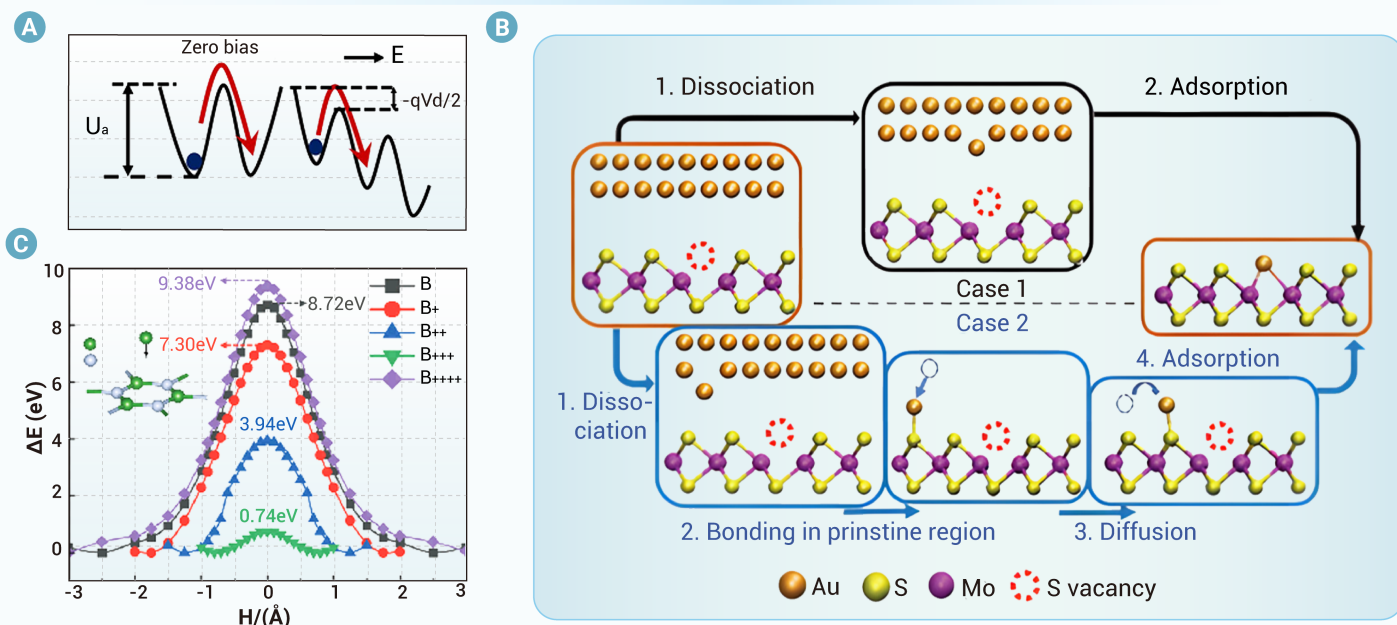


Figure 3. Schematic representation of the ion migration mechanism in 2D materials (A) The comparison of the migrating barriers of ions with and without an electric field. Adapted with permission.¹⁰⁷ Copyright 2019, Wiley-VCH. (B) Schematic of the dissociation-diffusion-adsorption model for Au ion migration in MoS₂. Adapted with permission.¹²² Copyright 2020, Wiley-VCH. (C) Migration barriers for B ions with different charges in h-BN. Adapted with permission.⁸⁹ Copyright 2024, Wiley-VCH.

And the ion mobility μ relates to D obeying the Einstein relation ($\mu = qD/kT$). n_D , D_0 , k , and T are the ion concentration, pre-exponential factor of D , Boltzmann's constant, and temperature, respectively.¹²⁰ Therefore, the efficiency of ion migration strongly depends on U_a . As the energy barrier U_a decreases, the ion mobility μ increases, leading to higher ion conductivity. Zhai et al. facilitated a 10.4 nm-thick AgCrS₂ flake that shows a large ionic conductivity of 192.8 mS/cm at room temperature,¹²¹ exhibiting the potential of 2D vdW materials for developing high-efficiency ion-driven electronic devices.

Moreover, the migration process in 2D materials involves not only diffusion and drift within the lattice, but also significant interaction with intrinsic defects, particularly vacancies, which act as localized traps that influence ion distribution and migration pathways. For metal ions, this interaction often follows a dissociation-diffusion-adsorption model (Figure 3B), in which metal ions can either adsorb onto vacancies or directly migrate before adsorption, forming localized conductive points that alter charge carrier pathways by reducing scattering.¹²² Furthermore, due to the layered structure of 2D materials, ion migration exhibits distinct behaviors depending on whether ions move within the 2D plane (in-plane migration) or across the layers (out-of-plane migration). The interaction between ions and defects varies across these two modes. These differences in migration pathways and defect interactions result in unique transport characteristics that are crucial for understanding both in-plane and out-of-plane ion migration in 2D materials.

Modes of ion migration

In-plane migration. In-plane ion migration primarily occurs through the vdW gaps between layers, resulting in low migration energy barriers and allowing ions to move more freely parallel to the atomic plane.¹²³ Due to variations in lattice arrangement and electrostatic interactions, ions favor pathways with weaker atomic bonding and lower diffusion barriers, exhibiting direction-dependent behavior.^{77,124,125} In addition, defects such as grain boundaries and vacancies significantly influence the in-plane ion migration pathways and kinetics in 2D materials by altering local atomic arrangements, electronic environments, and energy barriers.^{126–128} Grain boundaries facilitate in-plane ion migration by reducing the energy barriers,¹²⁹ and play a crucial role as pathways for ion migration. For instance, grain boundaries in MoS₂ mediate the in-plane ion migration, enabling resistance modulation. Their

geometries determine the switching behaviors of the MoS₂-based device: intersecting-grain boundaries allow bistable resistance states and bridge-grain boundaries facilitate pronounced negative differential resistance, with vacancy migration playing a key role.¹³⁰ Lee et al. reported that the laterally-interconnected 2D-SnO nano-crystallites include lots of charged states at grain boundaries, which would help the effective transport of both Ag⁺ ions and electrons, thus the migration pathways can be easily constructed inside the 2D layer.¹³¹ Grain boundaries govern the distribution of defects and the behavior of ion migration, which influences the electrical performance of 2D vdW materials-based devices. Controlling the crystalline orientation during the synthesis process effectively regulates in-plane ion migration, thereby enhancing the performance of ion-driven reconfigurable information and energy storage devices.

A vacancy results in the formation of a potential trap that captures migrating ions, hindering reversible in-plane ion migration. Taking Li⁺ ion migration in Mo₂C with Mo vacancies as an example, the Li⁺ ion is designed to move along the path from the top site of the Mo atom to its nearest neighboring Mo atom. Then it crosses the top site of the C atom to the vacancy site. The migration barriers of these two processes are 0.115 eV and 0.258 eV, respectively. The Li⁺ ion requires overcoming a high barrier of 0.93 eV to escape from the vacancy site; it will be trapped and probably cannot migrate reversibly.¹³² Actually, ions tend to diffuse at a flat surface with lower migration barriers and need to overcome larger obstacles to enter vacancy sites; hence, the influence of these potential traps on in-plane ion migration is limited. Additionally, vacancy engineering enables atomic-level directional control of ion migration in 2D materials. Through first-principles calculation, Wang et al. reported that the migration barriers of H⁺ ion in B-vacancy and N-vacancy h-BN are 1.83–2.47 eV and 1.71–2.30 eV, respectively, which are much larger than the 0.72 eV of intrinsic h-BN. The migration of H⁺ ions in h-BN can be directionally controlled by controlling the position of vacancies, which can be artificially constructed through defect engineering.¹³³ This method offers a novel approach to constructing next-generation ion-driven reconfigurable devices.

Out-of-plane migration. In 2D materials, out-of-plane ion migration is hindered by strong interlayer interactions, which require ions to cross dense atomic layers. These layers, characterized by strong chemical bonds and spatial constraints, create physical and electrostatic barriers, leading to

higher ion diffusion barriers than in-plane migration.¹³⁴⁻¹³⁶ For example, the activation energy for the Cu⁺ ion migrating in the in-plane direction of CuInP₂S₆ is 0.23 eV, which is significantly lower than the 0.85 eV in the out-of-plane direction.^{84,137} Actually, the migration across layers necessitates the transmission of ions through interstitial sites, frequently accompanied by temporary distortion or rupture of bonds within the 2D lattice.¹³⁸ Moreover, the ease of out-of-plane migration is closely related to the intrinsic structural characteristics of the 2D materials. Increased interlayer spacing or diminished interlayer coupling can result in wider migration channels, thereby reducing the diffusion barriers. In contrast, densely packed layers impose more substantial barriers. Thus, the interstitial gap size and the ionic radius emerge as pivotal factors that regulate out-of-plane ion migration. For instance, Li et al. utilized density functional theory to calculate the diffusion barriers of Ag⁺ ions migrating through graphene, PtTe₂, and InP₃ layers.¹³⁹ Their results indicate that the diffusion barrier in graphene (4.27 eV) and PtTe₂ (2.03 eV) is higher than that in InP₃ (0.22 eV). This difference mainly arises from variations in the atomic bonding strength of 2D materials, with Ag⁺ ions overcoming the highest barrier when migrating through the graphene due to its dense sp² hybridization.

Additionally, atomic-scale defects, such as vacancies, grain boundaries, and substitutional dopants, can locally disrupt the lattice structure, creating rapid pathways that facilitate ion penetration through the layers.^{109,140} Defect engineering has been widely employed to modulate out-of-plane ion migration in 2D materials, and a higher defect density facilitates the formation of migration paths.^{141,142} In almost defect-free h-BN (~1.0 × 10¹⁰ cm⁻²), it requires a relatively high voltage (8.7 V) to create Ag⁺ ion migration pathways randomly. As the defect density increases, migration paths are more likely to form at the defective regions, leading to a decrease in operating voltage and mitigating the stochastic formation of migration pathways. An optimized defect density (6.5 × 10¹³ cm⁻²) designed by Kang et al. results in self-confined vertical channels that minimize excess energy loss for Ag⁺ ion migration, which is necessary for ultralow-power operations.¹⁴³ Furthermore, the diffusion barrier is significantly influenced by the charge state of migrating ions. Electrostatic interactions between ions and lattice atoms can either impede or facilitate migration, depending on the materials and the charge of the ions. Du et al. reported that boron ion migration in h-BN becomes substantially easier when the ions carry a higher positive charge, effectively lowering the diffusion barrier (Figure 3C).⁸⁹ This charge-dependent behavior highlights the complex interplay among ion charge, lattice structure, and migration kinetics. Consequently, in-depth investigation of the relationships between material, defects, and ion charge provides valuable guidance for designing 2D materials with tailored ion transport properties for advanced applications.

Physical properties modulation of 2D vdW materials under ion migration

Ion migration induces changes in the composition, crystal structure, and other properties of 2D materials, often accompanied by a range of physical effects. These dynamic and non-destructive behaviors can be precisely controlled through electric fields, allowing for the efficient modulation of the fundamental physical properties of the 2D materials. To date, ions have been employed to modulate crystal phase, carrier concentration, band structure, and interfacial barriers in 2D materials under external electric fields. This real-time, field-programmable nanoionics technology provides a novel strategy for developing reconfigurable electronic devices.

Ion-induced phase transition. Charge-carrying ions intercalated or deintercalated in the vdW gap can interact with neighboring atoms in the 2D materials and transfer charge.¹⁴⁴⁻¹⁴⁶ This process alters the electronic structure of the 2D material, inducing a phase transition. A phase transition refers to the transformation from one phase structure to another, often accompanied by significant changes in physical properties, such as conductivity.¹⁴⁷⁻¹⁴⁹ It predominantly occurs in transition metal dichalcogenides (TMDs), MXenes, and black phosphorus (BP).¹⁵⁰⁻¹⁵³ For TMDs (e.g., MoS₂, WS₂, and WSe₂), various crystal structures have been observed, including 2H and 1T (or 1T') phase, which are attributed to differences in atomic bonding and the manner in which the layers are stacked. The 2H phase is characterized by a hexagonal structure with trigonal prismatic coordination of the metal atoms and typically exhibits semiconducting behavior, whereas the 1T (or 1T')

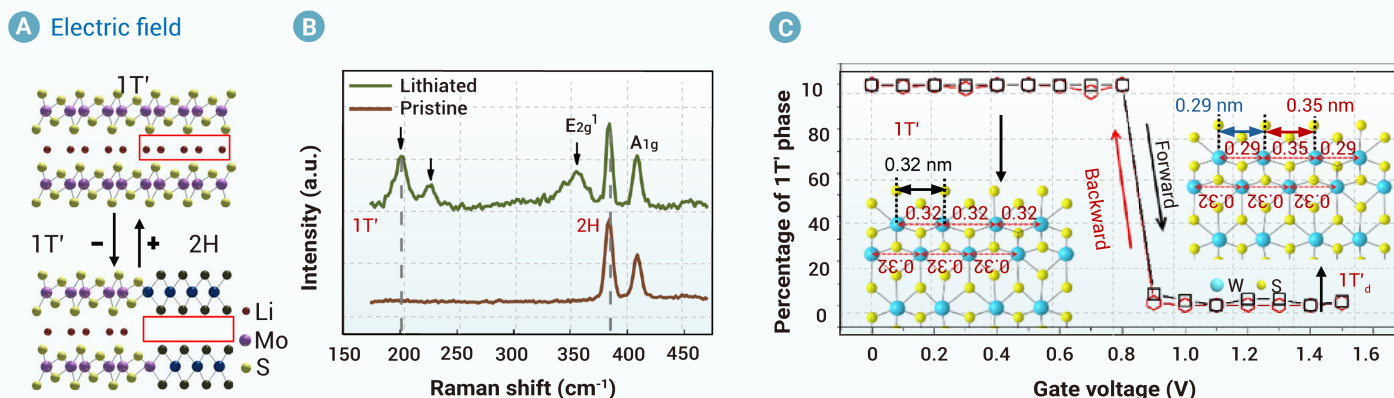
phase has a tetragonal structure with distorted octahedral coordination, exhibiting metallic behavior.^{154,155} The transformation between these phase structures can be achieved through controlling the ion migration.¹⁵⁶

Since Hearing et al. have demonstrated that the phase transition of MoS₂ can be induced by Li⁺ ions intercalation,¹⁵⁷ ion intercalation has become a common method for inducing phase transition in 2D materials.¹⁵⁸⁻¹⁶² Li⁺ ions can lead to the 2H → 1T' structural phase transition of MoS₂, due to electron transfer from the intercalated Li⁺ ion to Mo 4d orbitals that destabilizes the 2H phase,¹⁶³ and the conversion to the 1T' phase was verified by the appearance of the characteristic Raman peaks (200, 225 and 355 cm⁻¹).¹⁶⁴ Electric fields can drive the in-plane migration of Li⁺ ions and modulate the local Li concentration in a lithiated 1T'-MoS₂ film, resulting in reversible and localized phase transition between 2H and 1T' phase (Figures 4A-B).¹⁶⁴ Recently, Zhai et al. reported a reversible phase transition in the semimetallic 1T'-WS₂ driven by proton intercalation and deintercalation, and discovered a novel semiconducting 1T'_d-WS₂. Both 1T' phase and 1T'_d phase had a tetragonal structure with distorted octahedral coordination, with the difference lying in the distance between the W atoms in zigzag chains. The distance between W atoms was 0.32 nm in the 1T' phase, whereas in the 1T'_d phase, W atoms formed W dimers with distances of 0.29 nm and 0.35 nm (Figure 4C). Specifically, after applying a gate voltage exceeding 0.96 V in a 0.5 M H₂SO₄ aqueous electrolyte, protons intercalated into the vdW gaps of 1T'-WS₂ and injected ~1 electron per formula unit of WS₂. The electron injection modified the electronic configuration of W atoms, inducing the asymmetric displacement of W atoms in zigzag chains to generate one line of W dimers and thereby reconfiguring the lattice into the 1T'_d phase. Due to the reversible nature of ion intercalation and deintercalation, the 1T'-1T'_d phase transition of WS₂ was also reversible. A large switching ratio exceeding 10⁶ has been achieved during this process.¹⁶⁵ Therefore, the dynamic modulation of phase transitions in 2D materials provides a reversible approach that goes beyond conventional methods. It is of great significance in enhancing the functionality and application potential of 2D materials, such as contact resistance reduction, memory devices, energy storage, and sensors.

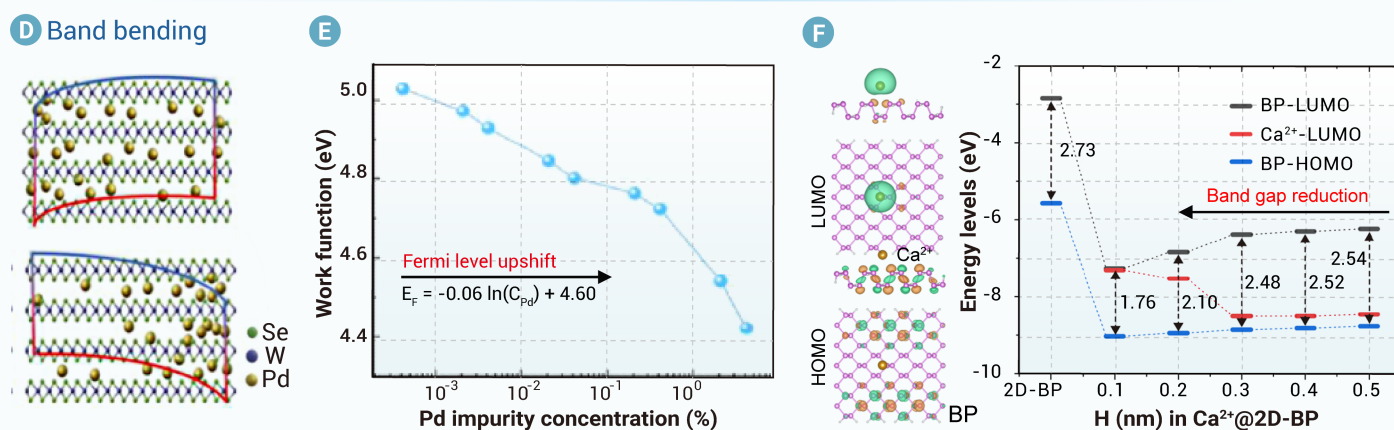
Ion-induced band structure modulation. Except for inducing phase transitions, ion migration can modulate the band structure of 2D materials. Ions introduced into 2D materials can act as electron donors or acceptors, and the resulting charge transfer alters the position of the Fermi level relative to the conduction band and valence band, directly affecting the band structure and carrier concentration.¹⁷⁰⁻¹⁷² For example, the migration of metal cations induces charge redistribution in 2D materials, due to charge transfer from the ions to the 2D material, which leads to significant electrostatic effects and charge accumulation within the material.^{173,174} Consequently, the Fermi level of 2D materials rises with the number of migrating ions.¹⁷⁵ Yang et al. revealed dynamic band structure modulation of WSe₂ by controlling Pd⁺ ion migration within its interlayers (Figure 4D).¹⁶⁶ Under positive or negative voltage, Pd⁺ ions accumulate near the cathode or anode, respectively. Calculations of the work function at varying Pd doping concentrations showed that the Fermi level of WSe₂ shifts toward the conduction band as ion concentration increases, indicating that Pd doping drives a transition to n-type semiconducting behavior (Figure 4E). Moreover, the extent of charge transfer primarily influences the ability of ions to modulate the band structure. For example, migration of monovalent cations (e.g., Li⁺, Na⁺) has minimal impact on the band gap, whereas divalent cations (e.g., Mg²⁺, Ca²⁺) can significantly reduce the band gap, suggesting enhanced charge transfer rates (Figure 4F).¹⁶⁷ Therefore, ion migration can effectively modulate the band structure of 2D materials, achieving reversible changes in critical parameters, including carrier concentration, band gap, and Fermi level position, offering a flexible and efficient strategy for modulating the performance of reconfigurable electronic devices.

Ion-induced interface barrier engineering. In addition to modulating the phase structure and band structure, ion migration can reversibly tune the interface barrier height of 2D material-based devices, enabling a reconfigurable rectification function.^{168,176} Under an applied electric field, ions migrate and accumulate at the edges of 2D materials, generating a localized and non-uniform potential gradient near the interface, thereby inducing band bending and changing the interface barrier height.^{89,177} For metal-2D semiconductor

Ion-induced phase transition of 2D materials



Ion-induced band structure modulation



Ion-induced interface barrier modulation

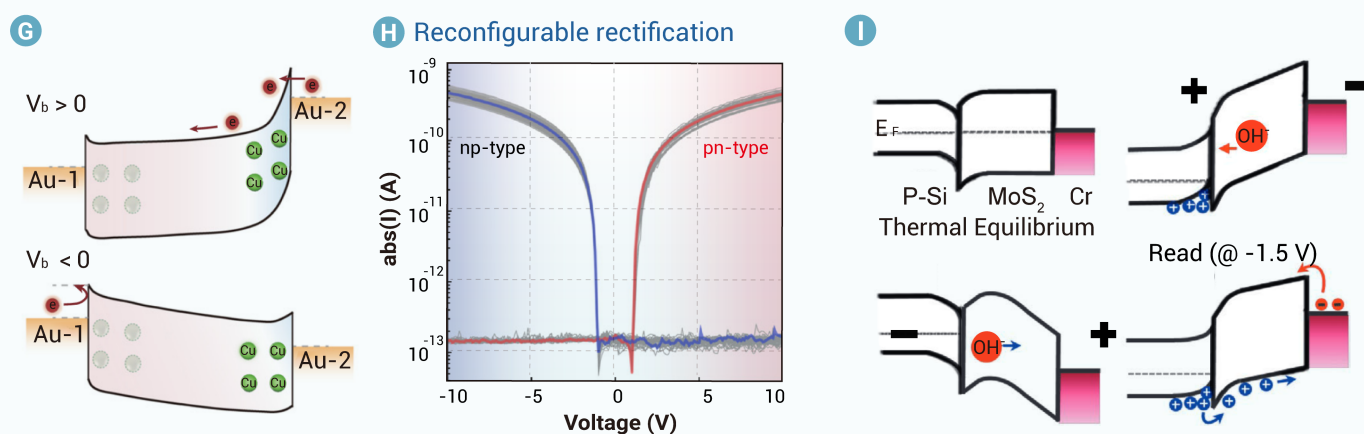


Figure 4. Modulation of the physical properties of 2D materials through nanoionics (A–B) Li^+ ions-induced phase transition of MoS_2 from $1\text{T}'$ to 2H , and the corresponding Raman spectra on the right. Adapted with permission.¹⁶⁴ Copyright 2018, Springer Nature. (C) Atomic structural models of $1\text{T}'$ - WS_2 and $1\text{T}'_d$ - WS_2 during the reversible phase transition, with the percentage of the $1\text{T}'$ phase being modulated under an electric field. Adapted with permission.¹⁶⁵ Copyright 2023, American Chemical Society. (D) Band bending of WSe_2 induced by non-uniform distribution of Pd^{2+} ions. (E) The influences of ion doping concentration on the Fermi level of WSe_2 . Adapted with permission.¹⁶⁶ Copyright 2025, American Chemical Society. (F) Modulation of the band gap in 2D materials by ion migration. Adapted with permission.¹⁶⁷ Copyright 2024, under a CC-BY license. (G) Modulation of interface barriers in 2D materials induced by ion migration and accumulation. (H) Cu^+ ion-induced reconfigurable rectification behavior in 2D materials. Adapted with permission.¹⁶⁸ Copyright 2025, Elsevier. (I) Regulation of charge carrier transport behavior at the interface of 2D materials by ion migration. Adapted with permission.¹⁶⁹ Copyright 2020, Wiley-VCH.

contacts, ion migration modulates the Schottky barrier height (SBH), which governs carrier injection efficiency.^{178–180} Specifically, the SBH decreases or increases depending on whether cations or anions accumulate, resulting in rectification behavior in 2D material-based devices. Under forward (reverse)

bias, ion migration reduces (increases) the SBH, facilitating (impeding) carrier transport, thereby increasing (decreasing) the current. For example, Zhong et al. reported a reconfigurable rectifier based on CuInP_2S_6 , where Cu^+ ion-induced band bending near the electrode modulates the metal-semiconductor

contact resistance, thereby exhibiting tunable rectification behavior (Figures 4G-H).¹⁶⁸ Belete et al. demonstrated that OH^- ion migration changes the barrier at the Si/MoS_2 interface, controlling charge transfer from Si to MoS_2 (Figure 4I). Calculations of the corresponding MoS_2 valence bands show that the hole barrier at the Si/MoS_2 interface decreases under negative bias due to OH^- ions being driven toward the interface, leading to enhanced carrier injection efficiency, and it increases under positive bias due to OH^- ions being pulled away from the interface, resulting in reduced injection efficiency.¹⁶⁹ Hence, the ion-induced interface barrier modulation directly leads to reconfigurable rectification behavior in 2D materials, allowing for the construction of multifunctional circuits that enable function switching without requiring changes to electrical components. This holds great promise for the fabrication of reconfigurable electronic devices.

Ion-induced local filament formation. The application of an electric field to drive the migration and rearrangement of external active metal cations (e.g., Ag^+ , Cu^{2+} , Ti^{2+}) or intrinsic ions (e.g., Cu^+ , S^{2-} , Se^{2-}) induces the formation of localized conductive filaments within 2D materials.^{108,181,182} Metal cations drift along low-energy pathways inside the confined vdW gaps, toward the cathode, where they gain electrons and are reduced to atoms through electrochemical reduction reactions. These atoms then aggregate to form clusters that continuously grow into metal-type filaments.¹⁸³⁻¹⁸⁵ In the absence of metal cations, intrinsic anions migrate toward the anode, creating positively charged vacancies along their pathways. As anions continue to migrate, these vacancies accumulate near the cathode, forming vacancy-type filaments.^{70,186-189} Owing to the high electrical conductivity of metal filaments and the defect energy levels associated with vacancy filaments, the efficiency of electron transport within 2D materials is greatly enhanced. Consequently, these filaments dominate the electrical properties of the 2D materials, effectively converting their semiconducting behavior into metallic behavior. When an opposite electric field is applied, these filaments rupture and regroup into discrete nanoparticles.^{190,191} This phenomenon opens up exciting opportunities to design and modulate the composition and structure of 2D materials in a highly reconfigurable manner.¹⁹² By carefully controlling the electric field, the width of ion-induced filaments can be reduced to only a few atoms. Together with the quantum confinement effect inherent to 2D materials, electron transport becomes restricted to this nanoscale region, providing an ideal platform for studying the electrical properties of one-dimensional (1D) nanostructures.

Ion migration in 2D materials can be reversibly controlled by an external electric field, offering exceptional potential to directly modulate their physical properties, including crystal phase, band structure, interface barrier, and the formation of conductive filaments. It enables dynamic tuning of carrier transport within 2D materials, leading to the reversible reconfiguration of electrical resistance. Therefore, devices based on 2D materials driven by nanoionics present a promising approach for the development of multifunctional, reconfigurable electronics.

RECONFIGURABLE RESISTANCE MODULATION BASED ON 2D MATERIALS

2D vdW materials have attracted considerable interest in modern electronics due to their unique electrical properties. The incorporation of mobile ions further enhances their functionality, enabling the development of robust, multifunctional, and reconfigurable devices. As discussed in Section 2, these materials are susceptible to ion migration, allowing for the reversible modulation of their electrical characteristics under the external electric fields. This capability facilitates tunable resistance states through reconfigurations of phase, band structure, carrier concentration, and interface barriers. Structural design strategies, which leverage ion migration dynamics within the vdW gap, can further modulate device resistance by varying the positions and number of device terminals.

Resistance switching modes

To gain a clear understanding of the resistive switching modes in ion-driven 2D materials-based devices, a representative two-terminal architecture was selected for investigation. This simple yet versatile configuration enables the exploration of various 2D materials and their resistance switching behaviors, offering clear insights into the underlying mechanisms.¹⁹³⁻¹⁹⁵ Resistance modulation primarily depends on the applied bias, which drives

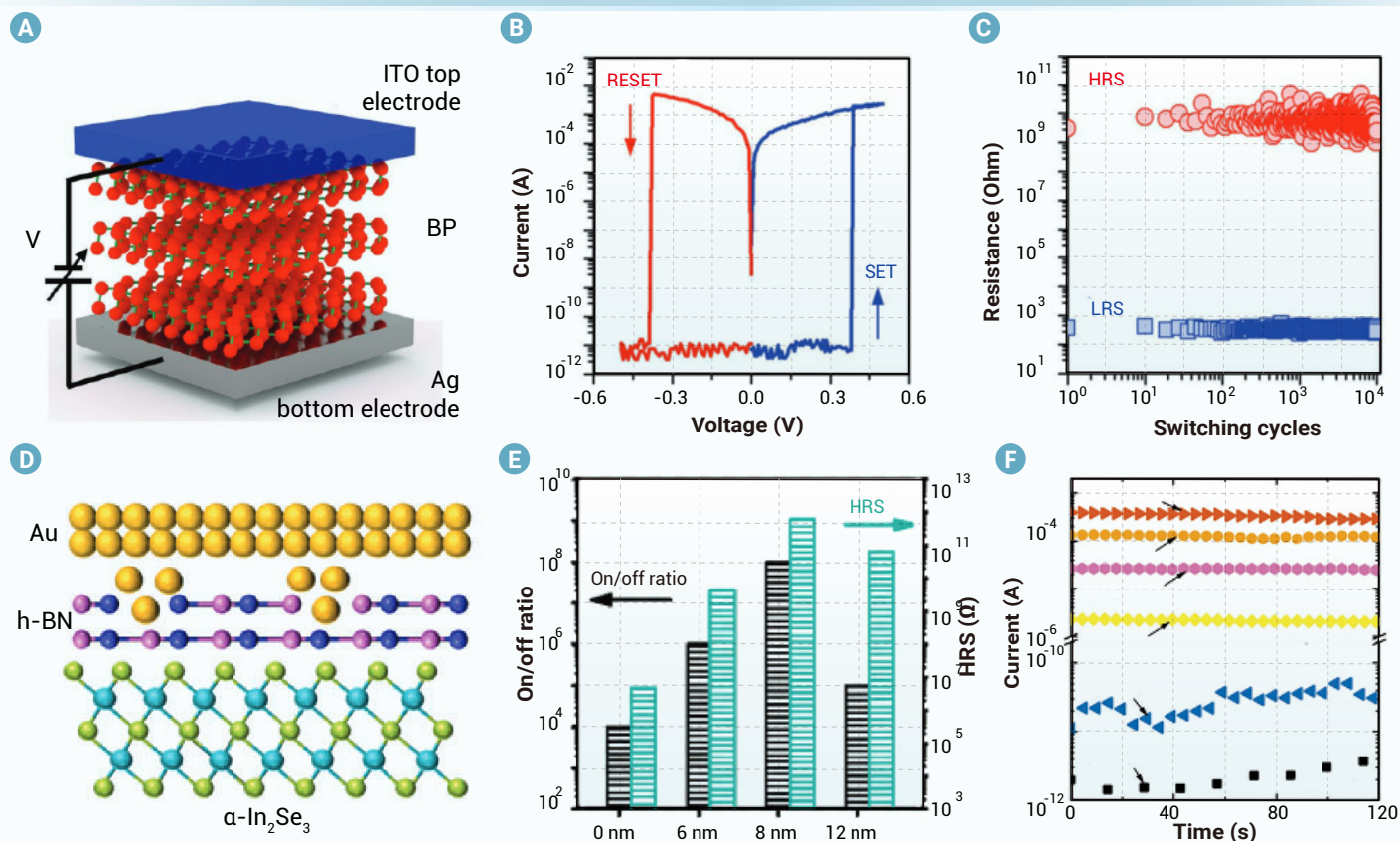
ion migration either within the 2D material or along its interfaces.¹⁹⁶ Depending on the stacking method relative to electrodes, devices are categorized into vertical or lateral structures, each exhibiting distinct resistance modulation modes. Vertical structures typically exhibit digital switching, characterized by abrupt and discrete transitions between high and low resistance states, whereas lateral structures display analog switching, featuring gradual and continuous resistance changes.^{197,198} These different resistance modulation modes influence the potential applications: digital switching is suitable for non-volatile memory, whereas analog switching is advantageous for neuromorphic computing.⁷⁶ It is crucial to understand and control these modes when designing next-generation reconfigurable 2D material-based electronic devices.

Digital switching. Digital switching in 2D materials-based devices refers to abrupt, discontinuous resistive switching behavior, where the device's resistance changes sharply and dramatically. It is described "digital" because the transition between the high resistance state (HRS) and the low resistance state (LRS) resembles binary steps, similar to the 0 and 1 states in digital circuits, making it widely used for rapid resistance modulation. The corresponding current-voltage (I-V) curve shows a sudden current surge at a threshold voltage, enabling swift and reversible transitions between the HRS and the LRS. This switching originates from filament formation and rupture within the 2D vdW materials. When the applied voltage exceeds a critical threshold, ions migrate rapidly and then accumulate to form filaments, drastically reducing resistance. A large number of studies have shown that digital switching mainly appears in devices with a vertical structure, which consists of the 2D material active layer sandwiched between source and drain electrodes (Figure 5A). In this unique structure, the interelectrode distance is reduced to the nanoscale or sub-nanoscale, which facilitates a strong, surface-perpendicular local electric field that drives the rapid ion migration along the field direction and controls their accumulation or depletion within the 2D materials.¹⁸² The formation or rupture of the filament during this process leads to abrupt current changes (Figure 5B). Recently, Ahmed et al. reported an ITO/BP/Ag device that exhibits an on/off ratio of 10^7 (Figure 5C) with good endurance.¹⁹⁹ Such high on/off ratios enable wide resistance adjustment ranges and strong immunity to resistance variations, supporting more distinguishable resistance states for high-density storage applications. This digital resistance switching provides steep turn-on characteristics of $< 1 \text{ mV dec}^{-1}$ and a high on/off ratio up to 10^{10} , which is widely used to fabricate selectors and memory devices to suppress sneak currents in passive crossbar arrays.²⁰⁰⁻²⁰²

Moreover, the bandgap of 2D materials has an obvious impact on digital switching. The carrier injection is commonly restricted by a wide bandgap, which can enhance interfacial electric fields and facilitate ion migration, thereby presenting faster and more energy-efficient digital switching.^{203,204} As a barrier layer, the electron transport and digital resistance switching behavior are directly affected by the thickness of 2D materials. The tunneling barriers for electrons increase with thickness, which further lowers the current of different states, possessing a significant impact on the on/off ratio of digital switching. Liu et al. reported that an 8 nm h-BN interlayer was used to suppress the off-state current, resulting in a large on/off ratio of 10^8 (Figures 5D-E).²⁰⁵ Electrons are transported through conductive filaments and subsequently tunnel across the h-BN interlayer. As the thickness of the h-BN layer increases, both the on/off current ratio and the HRS initially improve and then deteriorate. This trend suggests that tuning the thickness of 2D materials offers an effective strategy for optimizing the performance of digital switching devices.

Another significant factor affecting digital switching is the compliance current.^{76,90,105,206} The number of migrating ions in 2D materials is proportional to the magnitude of the compliance current. Consequently, multiple discrete intermediate resistance states within the device can be precisely realized.²⁰⁷ For example, Feng et al. reported an $\text{Ag}/\text{MoS}_2/\text{Ag}$ device with reconfigurable LRS ranging from 6.0 G Ω to 28 Ω through applying compliance current from 1 μA to 10 mA, while achieving 6 discrete resistance states (Figure 5F).²⁰⁸ Similarly, Yang et al. obtained 8 discrete resistance states in a MoTe_2 -based device.²⁰⁸ Shen et al. repeatedly programmed the resistance state of the MoSe_2 -based device to different levels, and successfully demonstrated the excellent reconfigurability of distinguishable resistance modulation through

Digital resistance switching



Analog resistance switching

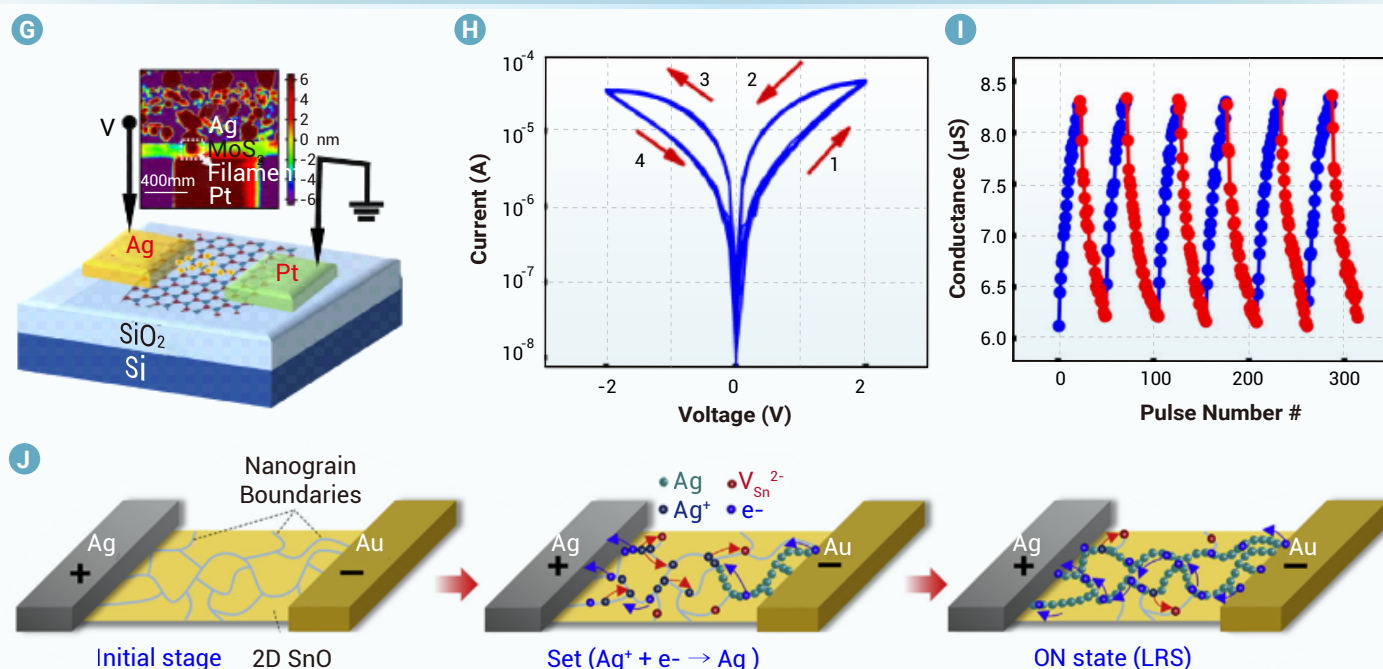


Figure 5. Ion-driven reconfigurable resistance modulation in a two-terminal device based on 2D materials (A) Schematic illustration of an ITO/BP/Ag device with vertical structure. (B) I-V characteristic sweep of the device in (A), which shows digital resistive switching. (C) Pulsed cyclic endurance of the device in (A) for $> 10^4$ switching cycles. Adapted with permission.¹⁹⁹ Copyright 2021, Wiley-VCH. (D) Schematic diagram of the interface of graphene/ α - In_2Se_3 /h-BN/metal memristor. (E) The current switching on/off ratio and the HRS values of the graphene/ α - In_2Se_3 /h-BN/metal memristor, with h-BN thicknesses of 0, 6, 8, and 12 nm, respectively. Adapted with permission.²⁰⁵ Copyright 2023, Wiley-VCH. (F) Schematic diagram of discrete resistance states modulated by compliance current. Adapted with permission.²⁰⁶ Copyright 2019, Wiley-VCH. (G) Schematic illustration of an Ag/MoS₂/Pt device with a planar structure. (H) Schematic diagram of analog resistive switching of the Ag/MoS₂/Pt device. (I) The continuous modulation of the resistance in the Ag/MoS₂/Pt device, by applying consecutive positive pulses (+2 V, 200 ms) followed by negative pulses (-2 V, 200 ms). Adapted with permission.¹⁰⁷ Copyright 2019, Wiley-VCH. (J) Schematic diagram of resistance changes caused by ions gradually migrating along grain boundaries on the surface of 2D materials. Adapted with permission.¹³¹ Copyright 2021, Elsevier.

digital switching.²⁰⁹

Furthermore, filament-mediated digital switching has been demonstrated to be a feasible method for controlling both non-volatile and volatile resistance modulation, enabled by the formation of stable and unstable filaments, respectively. Specifically, stable filaments maintain their structure after programming, with rupture primarily attributed to the out-diffusion of metal atoms into the host 2D materials due to electrochemical oxidation processes under reverse bias.^{210,211} Conversely, upon removing the bias and in the absence of any applied reverse voltage, unstable filaments spontaneously relax, resulting in their rupture and the subsequent reversion of the device to HRS.^{71,212,213} It is essential to clarify that these relaxation processes are primarily driven by the concentration gradient or surface energy minimization, particularly for filaments at the sub-10 nm scale with high surface-to-volume ratios.²¹⁴ These driving forces can induce ion relaxation and surface diffusion, which subsequently result in atomic clustering and eventual fragmentation into spherical nanoclusters. This process, identified as Ostwald ripening,²¹⁵ has been confirmed by molecular dynamics simulations and *in situ* transmission electron microscopy (TEM) observations.^{213,214,216}

Analog switching. Analog switching in ion-driven 2D materials-based devices refers to gradual, continuous resistive switching behavior without abrupt current jumps. It is described as “analog” because the resistance change takes place progressively, resembling the smooth transitions in analog systems. It enables refined modulation of the device's resistance, leading to multiple intermediate levels.^{217,218} It is particularly suitable for emulating synaptic weight modulation in neuromorphic systems.^{219,220} This behavior primarily occurs in lateral-structure devices, where source and drain electrodes align in the same plane as the 2D material (Figure 5G). Unlike digital switching, the I-V curve of analog switching shows a smooth transition with a small memristive hysteresis window and an on/off ratio typically below 10^2 (Figure 5H).^{77,166,169,221} The atomically confined channels provided by the layered structure allow ions to migrate within vdW gaps or along the 2D surface under a parallel electric field, forming dispersed conductive filaments. These filaments slightly reduce the resistance of the 2D materials, producing continuous analog states rather than direct transitions from HRS to LRS.²²² For example, Yin et al. reported that the conductance of the Ag/MoS₂/Pt device could be continuously potentiated and depressed by a series of positive pulses and negative pulses exceeding 300 cycles (Figure 5I).¹⁰⁷ Similarly, after applying consecutive voltage pulses to trigger the gradual migration of Cu⁺ ions, the CuInP₂S₆-based device showed linear states up to 1350 and low operation current of 100 pA, indicating its strong numeration ability and low energy consumption advantage.⁸⁴

Moreover, one of the critical performance metrics for analog switching is the linearity of resistance modulation, which equals 1 in the ideal case (linear conductance change). Linearity is defined as the consistency of the change in resistance state in response to input signals, such as the number of applied voltage pulses, indicating whether the resistance variation approximates a linear relationship. It has been demonstrated that the process is modulated by the pulse width and spike rate, where increasing either parameter results in an improved linear potentiation process. A high linearity of 1.07 has been demonstrated in a lateral MoS₂-based device,²¹⁹ which not only enhances the predictability and programmability of multi-level resistance states but also significantly mitigates the adverse effects of nonlinear mismatches in neuromorphic computing and other analog computing tasks. Meanwhile, the power consumed by each set pulse and read pulse is lower than 0.25 μ W and 2 nW, indicating the potential of analog switching for energy-efficient information devices. The grain boundary of the 2D surface plays a crucial role in facilitating the reliability of analog behavior in lateral devices by offering low-energy barrier sites,²²³ such as when Ag⁺ ions migrate along the grain boundaries of the intertwined nano-crystallites of 2D-SnO (Figure 5J), enabling continuous resistance changes.¹³¹ In lateral devices, the channel length is typically much greater than the channel thickness in vertical devices, which necessitates the application of higher operating voltages to drive ion migration effectively. Previous studies have demonstrated a positive linear relationship between the channel length and the applied voltage required to achieve the same current density.⁸⁴ Therefore, minimizing the channel length emerges as an effective strategy to realize low-power consumption analog switching in lateral ion-driven 2D material devices.

Interestingly, the resistance modulated through analog switching often exhibits a time-dependent decay after the electric fields are removed, due to ions gradually redistributing from their metastable positions.^{224,225} This relaxation behavior closely resembles the temporal response characteristics observed in biological synapses, where synaptic weights exhibit short-term plasticity and gradual decay over time. It allows 2D materials-based devices to emulate biological synaptic connections and complex neural processes easily. Hence, 2D materials-based devices exhibiting analog resistive switching present a promising hardware foundation for neuromorphic systems, enabling the development of intelligent information processing units that combine high efficiency, low power consumption, and strong adaptability for complex computational tasks.

Resistance modulation in multi-terminal configuration

Despite significant progress in resistance modulation of two-terminal devices, their single-input configuration limits the ability to control ion migration, thereby restricting the tunability of resistance states. Recent studies have shown that incorporating multiple terminals and spatially diverse electrode architectures enables more precise regulation of ion migration dynamics in 2D vdW materials.^{200,201,226–228} These multi-terminal devices primarily adopt structures similar to FETs, where more complex field-effect and electrochemical modulation can be achieved by introducing additional gate terminals.^{234,229,230} Through field-induced migration of ions or vacancies within the 2D materials, such architectures enable multilevel resistance modulation with enhanced endurance and reliability.²⁰⁰ This improved capability fosters the development of reconfigurable electronic devices with greater functional complexity and adaptability, promising significant advancements in next-generation information processing and memory technologies.

Building upon the enhanced control of ion dynamics enabled by multi-terminal configurations, this modulation offers transformative advantages that fundamentally enhance both the performance and versatility of resistive switching devices.^{231,232} It is feasible to achieve dynamic, real-time monitoring and precise control of the resistance state. Moreover, this approach supports simultaneous and decoupled read and write operations, effectively mitigating read-disturb effects by physically and functionally separating these processes.^{233,234} The device can be continuously monitored during programming or reconfiguration, addressing the critical issue of write-disturbance. For instance, Chung et al. demonstrated that a contralateral-gated MoS₂-based device exhibited outstanding stability, ultralow charge loss, and negligible read disturb degradation. The device achieved 55 distinct resistance states with near-zero nonlinearity, which is attributed to the physical separation of read and write terminals.²³⁵ This example demonstrates that a multi-terminal configuration is beneficial for enhancing the reliability of in-memory computing and neuromorphic applications, where uninterrupted data flow and real-time feedback are essential for efficient and adaptive information processing.

Moreover, the multi-terminal configuration introduces additional degrees of freedom for controlling resistive switching characteristics. It allows for the decoupled and independent modulation of the HRS and LRS, which is crucial for improving device reliability, functionality, and adaptability in emerging computing paradigms.^{236,237} Specifically, gate-mediated electrostatic doping enables precise and independent tuning of the HRS, providing enhanced control over the off-state behavior. Meanwhile, the compliance current applied at the drain terminal offers a robust modulation of the LRS, ensuring reliable and reproducible switching to the on-state. For example, Farronato et al. reported reconfigurable resistance modulation in a MoS₂-based device with a back-gate configuration. The results demonstrated that the HRS and LRS can be independently controlled by gate voltage and compliance current. The observed reduction in HRS at higher gate voltages was attributed to the increased electron concentration in the MoS₂ channel due to enhanced electrostatic doping. In contrast, the decrease in LRS with increasing compliance current was linked to the progressive growth of Ag conductive filaments (Figure 6A).²³⁶ They also demonstrated the select/unselect properties of this resistance modulation during programming and reading.

In addition to enhancing the on/off ratio, the multi-terminal configuration also facilitates reconfigurable tuning, providing greater flexibility and adaptability for electronics. It is advantageous for implementing neuromorphic

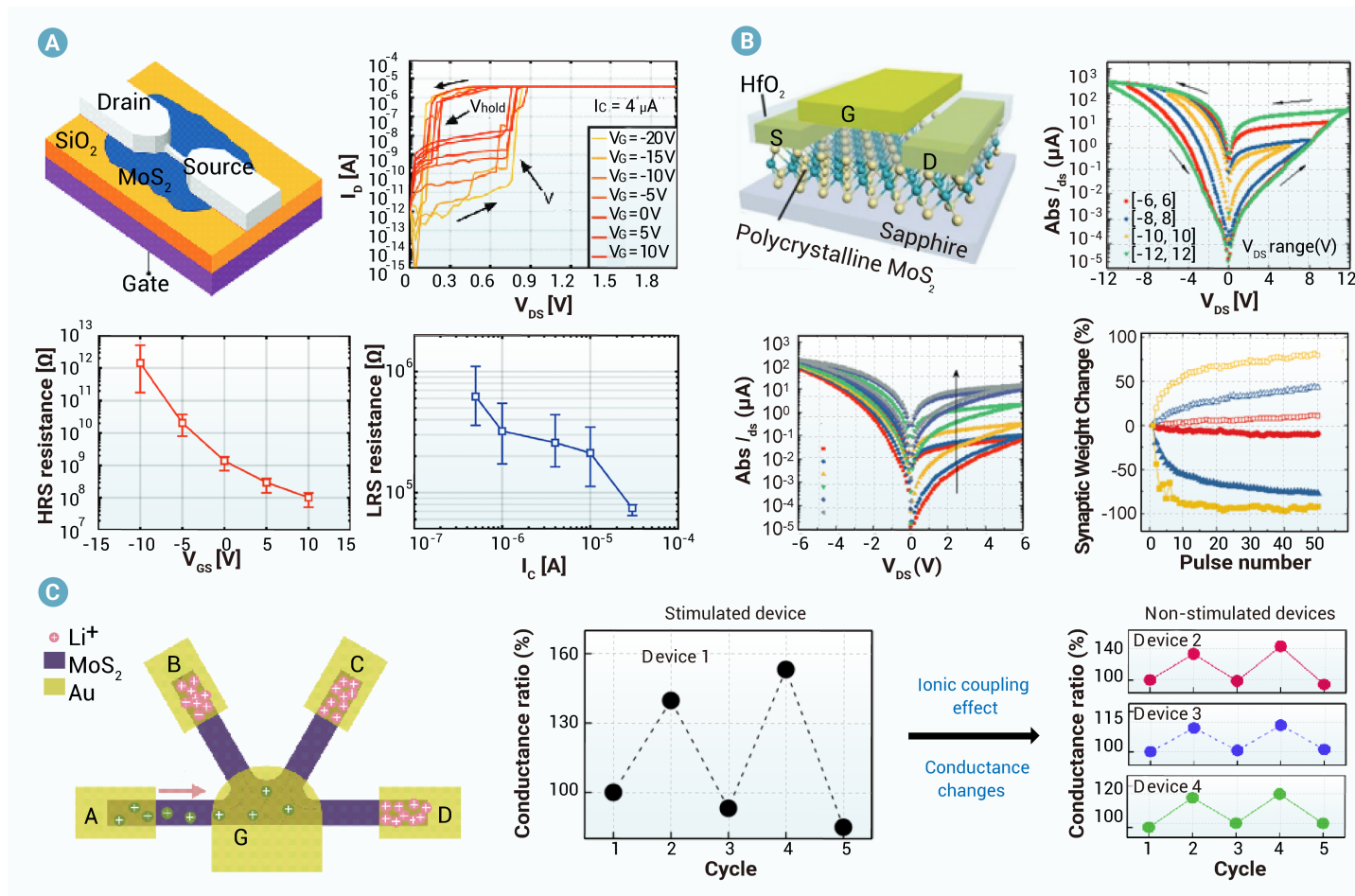


Figure 6. Ion-driven resistance modulation in a multi-terminal structure based on 2D materials (A) Schematic diagram of a MoS₂-based device with a back-gate electrode, and the reconfigurable modulation of HRS by gate-source voltage and LRS by compliance current. Adapted with permission.²³⁶ Copyright 2022, Wiley-VCH. (B) Schematic diagram of a MoS₂-based device with a top-gate electrode, and the results of reconfigurable resistance states regulated by drain-source voltage and gate-source voltage, respectively. Adapted with permission.²³⁷ Copyright 2019, Wiley-VCH. (C) Schematic diagram of a five-terminal Li₁MoS₂-based device with ionic coupling effect, consisting of four planar devices sharing a common gate, and continuous changes of reconfigurable conductance states controlled by a voltage pulse in one of the devices, which can modulate the conductance of other devices. Adapted with permission.¹⁶⁴ Copyright 2018, Springer Nature.

computing, where signal-dependent responses and multi-terminal coordination are essential. For example, Wang et al. reported a MoS₂-based device with a top-gate terminal, which exhibited source-drain voltage-dependent behaviors and gate-tunable resistive switching characteristics (Figure 6B).²³⁷ The on/off ratio increased from 34 to 1×10^4 as the sweeping source-drain voltage was raised from ± 6 V to ± 12 V, but decreased from 1×10^3 to 10 with increasing gate voltage. Utilizing this gate-controllable resistive switching, the synaptic plasticity simulations were achieved through modulating the resistance as a function of electrical pulse number and amplitude, demonstrating tunable synaptic weight updates under varying stimulation conditions. Additionally, Hu et al. demonstrated an all-2D-materials-based device capable of performing multiple neuromorphic operations by reconfiguring output terminals in response to stimuli.²³⁸ The realization of these complex functions relied on the ability to modulate resistance states in a reconfigurable manner.

Furthermore, the migration direction of ions within the vdW gaps can be effectively modulated by changing the electrode orientation of multi-terminal devices. This approach demonstrates that spatially controlling ionic transport pathways introduces new design flexibility for reconfigurable architectures, presenting great potential in the fabrication of multifunctional and adaptive electronic devices. For example, in a five-terminal device composed of four Li₁MoS₂-based devices sharing a common electrode, Li⁺ ions were distributed across the device and shared among the four terminals. The local Li⁺ concentration at each terminal could be precisely controlled by applying bias voltages to different terminals. Remarkably, its own resistance would be modulated when a voltage was applied to a single input terminal, as well as those of the other interconnected elements via ionic redistribution (Figure 6C).¹⁶⁴

This effect is attributed to ionic coupling through shared conduction pathways, resembling synaptic interactions in biological neural networks. More importantly, the concept of ionic-coupling-induced reconfigurable modulation can be generalized to other vdW materials with mobile ions, thus paving the way for the implementation of artificial neural networks. It is of great significance for brain-inspired electronics design, offering new opportunities for neuromorphic computing, adaptive logic circuits, and dynamic memory architectures.

2D materials enable reconfigurable resistance modulation through reversible ion migration under the influence of electric fields. Ions migrate laterally or vertically within vdW gaps, guided by structural design and the orientation of the electric field. Two-terminal configurations, valued for their simplicity in fabrication, support both reconfigurable discrete (digital) and continuous (analog) resistance switching. Multi-terminal architectures offer additional degrees of freedom, facilitating complex operations and enhancing device functionality. These highly tunable resistance states make ion-driven 2D material-based devices increasingly vital for applications in machine learning, bio-inspired electronics, and emerging quantum technologies.

APPLICATIONS

Electric field-driven ion migration enables precise resistance modulation in 2D material-based devices, facilitating dynamic reconfiguration of functions and offering significant potential for advanced information devices.^{239–241} These devices enable controllable electron transport at the atomic scale, promoting the development of highly integrated and miniaturized electronic devices. Precise resistance state control enhances operational accuracy and

stability, while allowing for fast dynamic responses, low power consumption, and stable multifunctional configurations that overcome the limitations of fixed structures.^{238,242-245} This reconfigurability allows real-time adaptation to diverse applications, increasing versatility and reducing hardware complexity. Therefore, ion-driven 2D material-based devices promise high-performance, multifunctional, and reconfigurable information technologies.

Memory

The formation and rupture of ion-induced local filaments enable the device to exhibit LRS and HRS, and the implementation of storage becomes achievable by assigning the binary values "0" and "1" to the HRS and LRS, respectively. The ability to scale 2D material thickness down to a few layers presents a promising opportunity to facilitate rapid filament dynamics, enabling high-speed, energy-efficient, and miniaturized memory devices with outstanding performance metrics. To date, the shortest switching speed (120 ps) among 2D memory devices has been observed in a h-BN memristor, with a low switching energy of 2 pJ.⁶⁹ More importantly, the strong covalent bonds in 2D materials endow the memory with excellent thermal stability. Wang et al. reported a robust graphene/MoS_{2-x}O_x/graphene memory that exhibits excellent switching performance with endurance exceeding 10⁷ cycles. Both HRS and LRS can remain stable for over 10⁵ s at a high operating temperature of 340 °C, suggesting potential applications of 2D memory in future high-temperature harsh electronics.⁷⁰ Furthermore, the storage density can be significantly enhanced through array configuration. The wafer-scale, high-density memory crossbar arrays have been fabricated using h-BN as the resistive switching layer, and the arrays exhibit a high yield (98%), low cycle-to-cycle variability (1.53%), and low device-to-device variability (5.74%).⁷¹ Thus, it is feasible to write and store image information in crossbar arrays.^{246,247} A 10 × 10 BP-based memory crossbar array has been demonstrated to write and store the letters "H", "U", and "N" separately, with each memory unit defined as an independent pixel.²⁴⁷ This high-density memory at array level provides the hardware foundation for next-generation information processing.

Notably, when the thickness of the 2D material active layer decreases to a monolayer, introducing a single metal atom in or removing it from a vacancy can markedly modulate the resistance of the device, an emergent device known as atomristor.²⁴⁸ This extreme sensitivity enables precise control of the resistance at the atomic scale, representing a breakthrough in memory technology. It effectively overcomes the thickness limitations and offers promising applications in ultra-compact energy-efficient storage, since the resistance states can be switched cyclically and retained without a power supply.²⁴⁸⁻²⁵¹ The atomristor was first demonstrated by Akinwande et al. in a vertical Au/monolayer MoS₂/Au device with non-volatile resistive switching behavior, and both the HRS and LRS had stable retention over a week at room temperature (Figure 7A).²⁴⁸ In another study, they revealed the mechanism of the atomristor. The substitution of metal atoms into sulfur vacancies resulted in non-volatile changes in resistance (Figure 7B).²⁵² Compared with monolayer MoS₂, the one-atom-thin h-BN film further reduces the vertical scaling to 0.33 nm and has been used to fabricate the thinnest memory. Wu et al. reported a h-BN atomristor with a large on/off ratio (10⁷) and rapid switching speed (< 15 ns) for accurate data storage, holding broad application prospects in next-generation miniaturized memory devices.²⁵³

In addition, the non-volatile, multi-level resistance states of 2D material-based devices have been used to achieve multi-bit memory, thereby fundamentally increasing storage density.²⁵⁴⁻²⁵⁶ Li et al. reported a MoS₂/h-BN/MoS₂/graphdiyne oxide/WSe₂ memory with an ultrahigh operation speed (20 ns), a low operation voltage (2 V), and an ultralow energy consumption (10 fJ). By adjusting the amplitude of the write voltage pulse, the conductive filaments within the device can effectively control the injection of electrons from WSe₂ to MoS₂, allowing the resistance of the device to be modulated to various levels. Based on this principle, they demonstrated 8 distinct storage levels with excellent retention over 10⁴ s, which can be used for 3-bit storage. The memory was programmed to the "111" state by a positive voltage pulse, while the other seven states of "110" to "000" could be reconfigured by applying negative voltage pulses (Figure 7C).²²⁸ Critically, the precision of ion migration in 2D materials enables storage capacity to be significantly expanded beyond 3 bits.²⁵⁷ These studies indicate the remarkable capability

of 2D material-based memory to achieve high-density, energy-efficient storage.

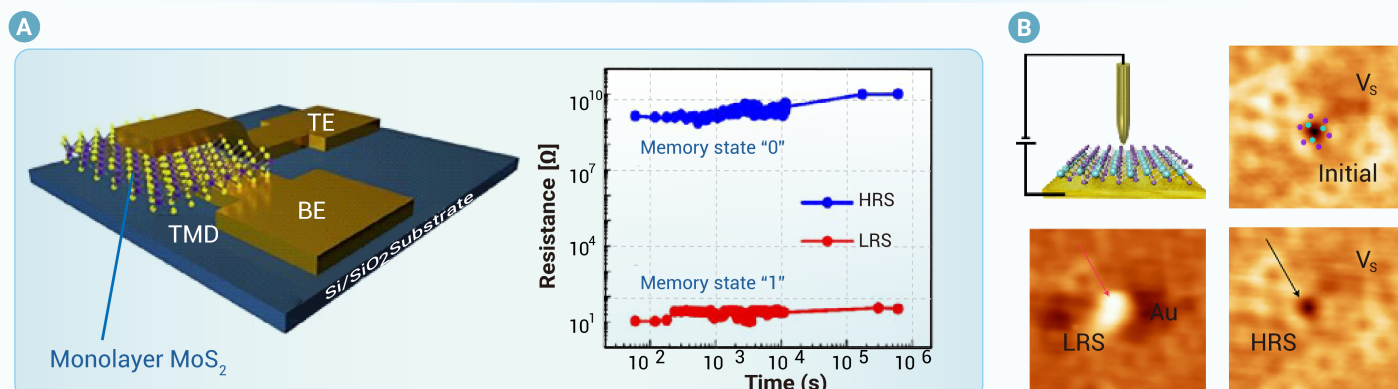
To further enhance the storage density, the design of stacked memory architectures has been broadly investigated.^{187,258-260} Memory based on 2D vdW materials delivers a promising candidate due to its atomic-level miniaturization capability and potential for heterogeneous integration. Its unique structure and properties allow for the vertical integration of memory units, significantly increasing the number of storage layers within a limited footprint. Tang et al. fabricated a 3D stacked MoS₂-based memory, where each layer of the MoS₂ memory stack is accessible and programmable independently. With these properties, a monolithic 3D circuit-based approach was proposed (Figure 7D).²⁶⁰ Similarly, Sivan et al. proposed a high-density 3D monolithic stacked WSe₂-based memory, which consists of a 1T1R cell integrating a surface-functionalized WSe₂ FET and solution-processed WSe₂ Resistive Random Access Memory (RRAM).¹⁸⁷ The authors demonstrated its good compatibility with CMOS processes and achieved high-density storage (Figure 7E). Thus, the 3D stacked 2D material-based memory not only improves space efficiency but also enables faster data access and processing speeds, making it a promising solution to meet the growing demands for data storage in the big data era.

Logic-in-memory

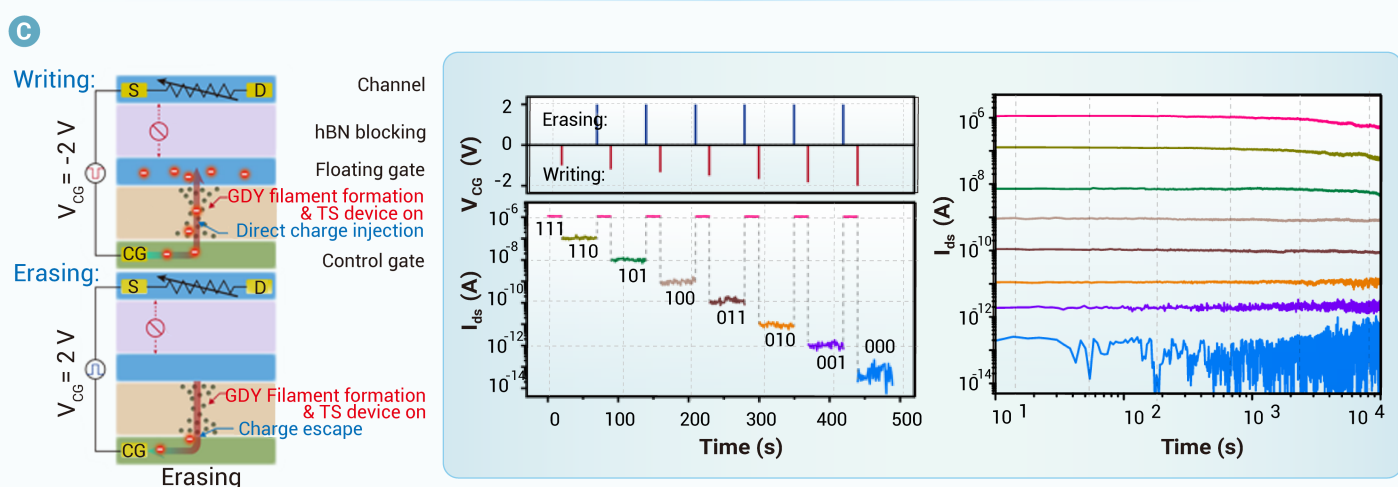
By integrating memory and processing functionalities into a single unit, in-memory computing minimizes the latency and energy consumption associated with data transfer, resulting in highly parallel and energy-efficient information processing.²⁶¹⁻²⁶³ Recently, ion-driven 2D materials-based devices have been demonstrated to perform Boolean logic, enabling multiple reconfigurable logic operations.²⁶⁴⁻²⁶⁶ These devices significantly reduced the footprint of logic circuits, while their rapid switching speed and substantial on/off ratio facilitate logic operations in a manner that is both efficient and reliable. Ion-induced rectification and resistance modulation can be employed to fabricate reconfigurable logic gates. Dynamic switching between OR and AND logic functions within a fixed circuit has been achieved by modulating the rectification behavior of two CuInP₂S₆-based devices.¹⁶⁸ This process involved regulating Cu⁺ ion migration to modulate the interfacial potential, thereby reversing the polarity of the devices. In the OR mode, the two devices were tuned to pn-type and np-type by applying a 20 V and a -20 V bias, respectively. Using the common electrode as output and the other two as inputs, the output voltage reached a high level (logic "1") when either input voltage was high (5 V, logic "1"). It dropped to 0 V (logic "0") when both input voltages were low (logic "0"), consistent with the truth table of OR logic (Figures 8A-C). Moreover, the large breakdown voltage of 170 V and ultralow leakage current of 100 fA of the device provide reconfigurable 2D logic circuits with the advantages of low energy consumption and strong anti-interference capability.

In addition, the ion-driven 2D materials-based devices with a vertical structure enable the realization of various logic functions within a single device, leading to a reduction in the number of devices required for logic-in-memory and the elimination of unwanted energy consumption. An Ag/In_{3/4}P₂S₆/Au device has been demonstrated to implement 14 distinct logic operations (e.g., NIMP, NOT, AND, NAND) by changing the applied voltage signals to two terminals, where the formation and rupture of voltage-controlled Ag filament were the driving forces behind the implementation of logic-in-memory (Figures 8D-F).²⁶⁷ The two logic variables were defined as "0" or "1", corresponding to low (0V) or high (2V) voltage levels applied to the device terminals. The LRS and HRS of the device represented output logic values "1" and "0", respectively. Logic operations were executed by applying specific voltage pulse sequences designed based on the truth table, and the output current reflected the computed result. Thus, different logic operations could be configured by varying the input voltage pulse sequences, demonstrating the feasibility and reliability of ion-driven 2D materials-based devices as logic-in-memory hardware. Furthermore, these memory devices can be readily integrated into crossbar arrays, where any single unit can be selectively addressed to execute different logic operations, showing significant potential for the realization of high-density, multifunctional logic-in-memory blocks. Liu et al. reported a HfSe₂-based crossbar device as a promising candidate due to its outstanding resistive switching characteristics, including a large

Atomristor



Multi-bit memory



3D stacked integrated memory

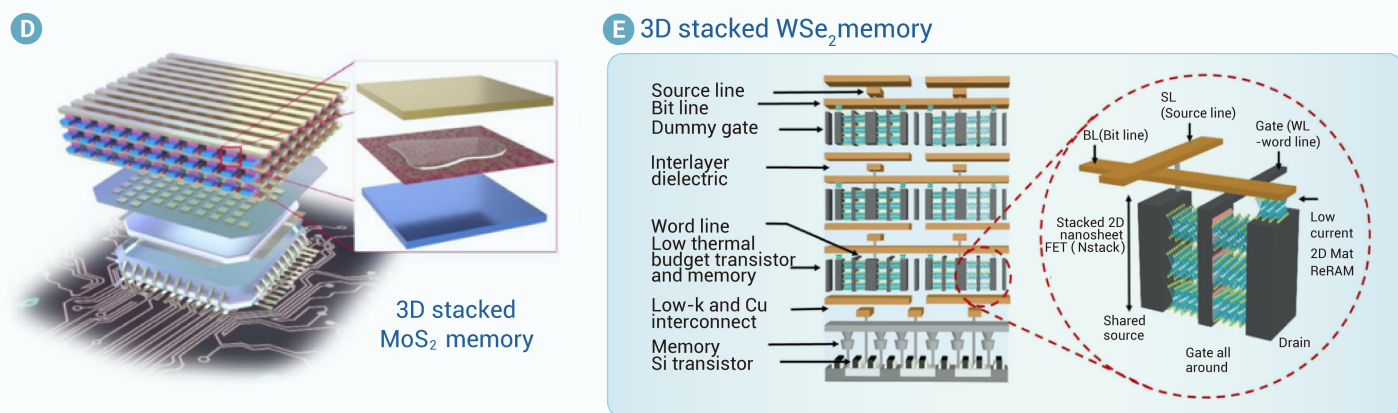


Figure 7. Memory based on reconfigurable resistance modulation (A) Schematic of an atomristor with the metal/monolayer MoS_2 /metal structure, as well as the retention of HRS and LRS. Adapted with permission.²⁴⁸ Copyright 2018, American Chemical Society. (B) The *in situ* scanning tunnelling microscopy images, which reveal the evolution of the sulfur vacancy in monolayer MoS_2 during the switching process of the atomristor. Adapted with permission.²⁵² Copyright 2020, Springer Nature. (C) The operation mechanisms of the $\text{MoS}_2/\text{h-BN}/\text{MoS}_2/\text{graphdiyne oxide}/\text{WSe}_2$ memory, and its 8 distinct resistance states modulated by voltage pulses for 3-bit storage, all of which can maintain over 10^4 s. Adapted with permission.²²⁸ Copyright 2022, Springer Nature. (D) Schematic diagram of 3D stacked $\text{Ti}/\text{MoS}_2/\text{Pt}$ memory with buried metal interconnects and logic circuits. Adapted with permission.²⁶⁰ Copyright 2022, Springer Nature. (E) Illustration of 3D monolithic stacking of CMOS logic and 3D-stacked WSe_2 memory. Adapted with permission.¹⁸⁷ Copyright 2019, Springer Nature.

on/off ratio ($> 10^3$), fast switching speed (< 50 ns), small operating current (100 pA), and low energy consumption (ranging from 0.1 fJ to 0.1 pJ) (Figures 8G–I). By modulating the migration of oxygen vacancies within the HfSe_xO_y layer, they successfully demonstrated in-memory computing with

XOR, IMP, and NAND operations, all of which aligned well with the corresponding truth table.²⁶⁸ However, these studies remain at the level of device implementation. Future research should focus on further verifying the logic operations in high-density integrated crossbar arrays.

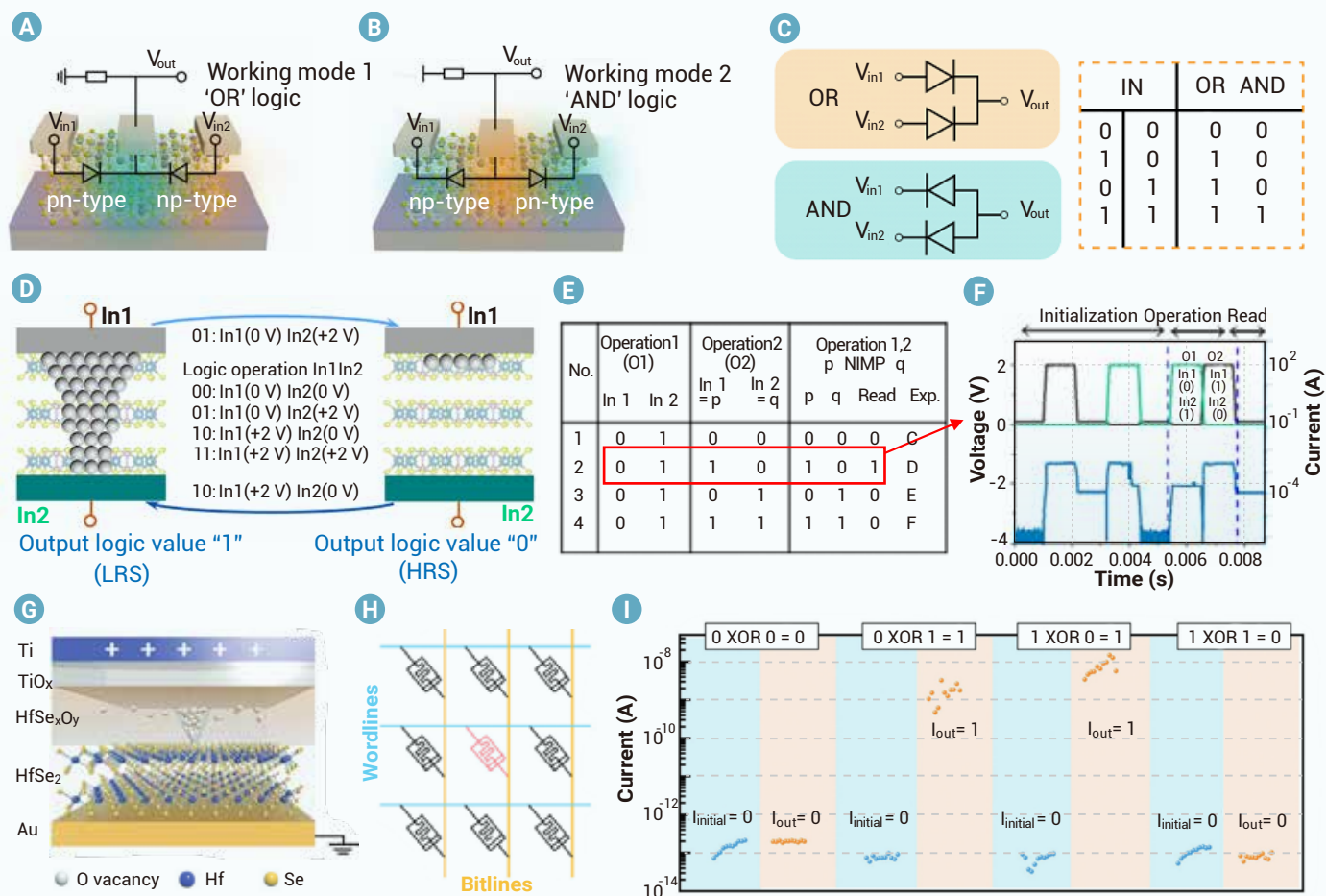


Figure 8. Logic-in-memory based on reconfigurable resistance modulation (A–B) Schematic diagram of working mode switching between OR and AND logic by modulating the migration of Cu^+ ions within CuInP_2S_6 , with input connections remaining unchanged. (C) Schematic of the logic circuit alongside the truth table of OR and AND logic operations. Adapted with permission.¹⁶⁸ Copyright 2025, Elsevier. (D) Logic operations by a single $\text{Ag}/\text{In}_{3/4}\text{P}_2\text{S}_6/\text{Au}$ device. (E) The truth tables and the operation sequence for the NIMP logic operation. (F) Experimental demonstration of the 1 NIMP 0 = 1 logic operation corresponding to the red box in (E). Adapted with permission.²⁶⁷ Copyright 2024, The American Association for the Advancement of Science. (G) Schematic illustration of $\text{Ti}/\text{HfSe}_2\text{O}_x/\text{HfSe}_2/\text{Au}$ device. (H) Schematic of the logic circuits. (I) Experimental results of the XOR logic operation by the device in (G). Adapted with permission.²⁶⁸ Copyright 2021, Wiley-VCH.

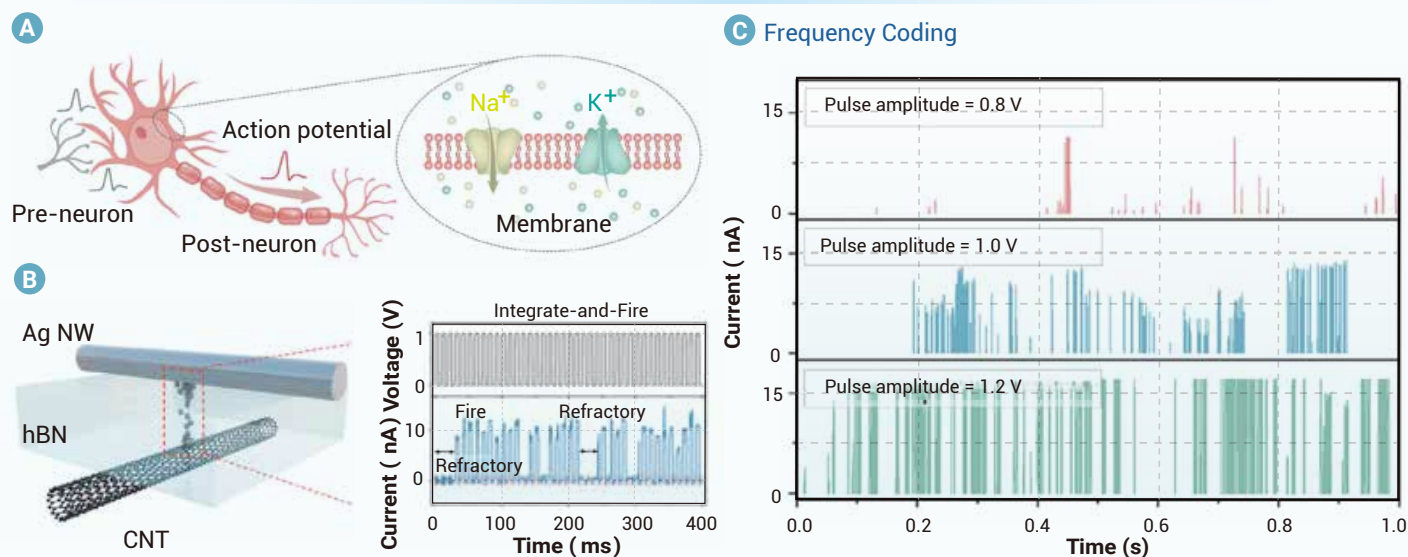
Neuromorphic computing

As another computational paradigm for in-memory computing, neuromorphic computing takes inspiration from the architecture of the biological human brain, where neurons collect and integrate electrical signals through synaptic connections.^{269–271} When these signals reach a certain threshold, the neuron generates an action potential, which is transmitted to the next neuron via the axon. The strength of these signals is modulated based on synaptic weight, either enhancing or diminishing the transmission. The introduction of 2D materials offers anisotropic ion transport properties, facilitating ion migration and coupling between devices. Benefiting from their inherent reconfigurable resistance, ion-driven 2D materials-based devices can simulate neuronal functions and neural network architectures, offering opportunities to construct reconfigurable neuromorphic devices with simple circuitry and low energy consumption.^{84,272–274} For example, Hu et al. simulated neuronal functions using digital resistive switching in a carbon nanotube/h-BN/silver nanowire cross-point structure (Figure 9A).²⁷⁵ The amount of Ag^+ ions was limited by the ultra-small active area (120 nm^2), resulting in the formation of thin and unstable Ag filaments (Figure 9B). Under a continuous voltage pulse train, the device demonstrated the ability to simulate the integrate-and-fire function. The spike excitation frequency was further co-modulated to realize frequency encoding by changing the input width and interval of the pulse (Figure 9C). Notably, the power consumption within a single spike cycle was only 4.85 nW. Combined with the ultra-small size of the device, this fully demonstrates the advantages of ion-driven 2D materials in realizing energy-efficient and miniaturized neuromorphic devices, providing a solid foundation

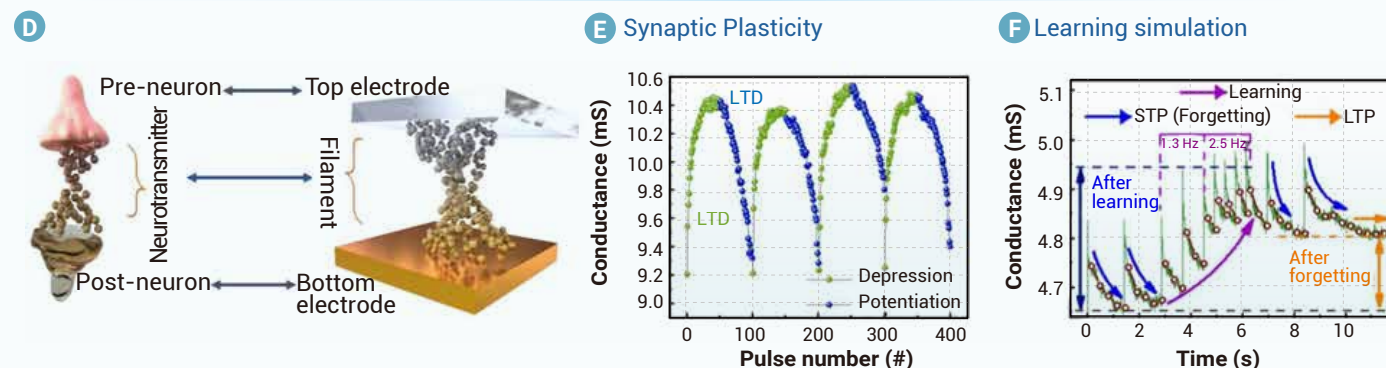
for the development of next-generation electronic devices.

The synapse serves as the connection between neurons, facilitating information processing through the transmission of neurotransmitters.²⁷⁶ Ion-driven 2D material-based devices primarily rely on external electrical stimuli to induce the migration of metal ions or vacancies. The resistance changes caused by the formation and rupture of conductive filaments can effectively mimic synaptic behaviors (Figure 9D).^{250,277} Among these, synaptic plasticity plays a pivotal role in information transmission, including long-term potentiation (LTP) and long-term depression (LTD), which involve synaptic weight updating over extended periods. Moreover, short-term potentiation (STP) and short-term depression (STD) help the synapse recover more quickly to its original state.^{278,279} Lee et al. presented the coexistence of STP and LTP by applying the Au-atom-relaxation phenomenon in the $\text{Au}/\text{MoS}_2/\text{Au}$ device.²⁵⁰ The resistance of the device increased or decreased with continuous positive or negative voltage pulses, respectively, closely mimicking LTP and LTD behaviors of synapses (Figure 9E). By changing the programming pulse width and amplitude to simulate different frequencies and strengths, the relaxation behavior of Au^+ ions can be well controlled, and they demonstrated the transition from STP to LTP, perfectly mimicking the learning and memory functions of the human brain (Figure 9F). Ren et al. reported the reconfigurable LTP and LTD behaviors exhibited by Te/WS_2 heterojunctions, enabling the emulation of an artificial perception system.²⁸⁰ Defects at the interface of the heterojunctions can capture or release charge carriers by applying a gate voltage, allowing the device to simulate synaptic plasticity. Subsequently, a classification accuracy of 90.5% for MNIST handwritten digit images was

Simulation of neuronal function



Simulation of synaptic function



Simulation of neural network architecture

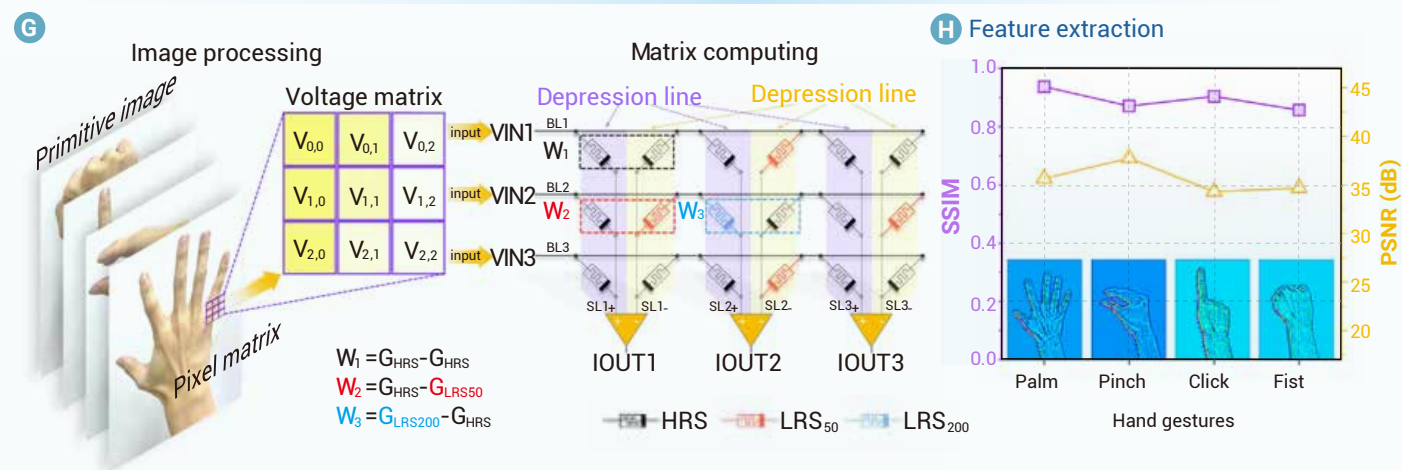


Figure 9. Neuromorphic computing based on reconfigurable resistance modulation (A) Schematic diagram of the information processing flow of biological neurons in the human brain. (B) Schematic illustration of the CNT/h-BN/Ag NW structure, which successfully simulates the integrate-and-fire behavior of a biological neuron. (C) The integrate-and-fire characteristics of the device in (B) at different voltage pulse amplitudes, and the spike firing frequency can be modulated by the voltage. Adapted with permission.²⁷⁵ Copyright 2025, Wiley-VCH. (D) Schematic of the imitation between a synaptic neural structure and device synaptic plasticity, and the change in device resistance can simulate the change of synaptic weight. (E) Schematic diagram of the LTP and LTD behaviors simulated by the Au/MoS₂/Au device. (F) Learning simulation result of Au/MoS₂/Au device. Adapted with permission.²⁵⁰ Copyright 2024, American Chemical Society. (G) Overall process of the gesture image convolution with the Cu_2S -based crossbar array. (H) The comparison of the hardware and software processed gesture images using the Laplacian kernel. Adapted with permission.⁹⁰ Copyright 2025, Elsevier.

obtained through neural network simulation.

In addition, the reconfigurable resistance modulation in ion-driven 2D

materials-based devices enables the imitation of continuous weight updates in neural networks. For example, Jo et al. demonstrated the hardware imple-

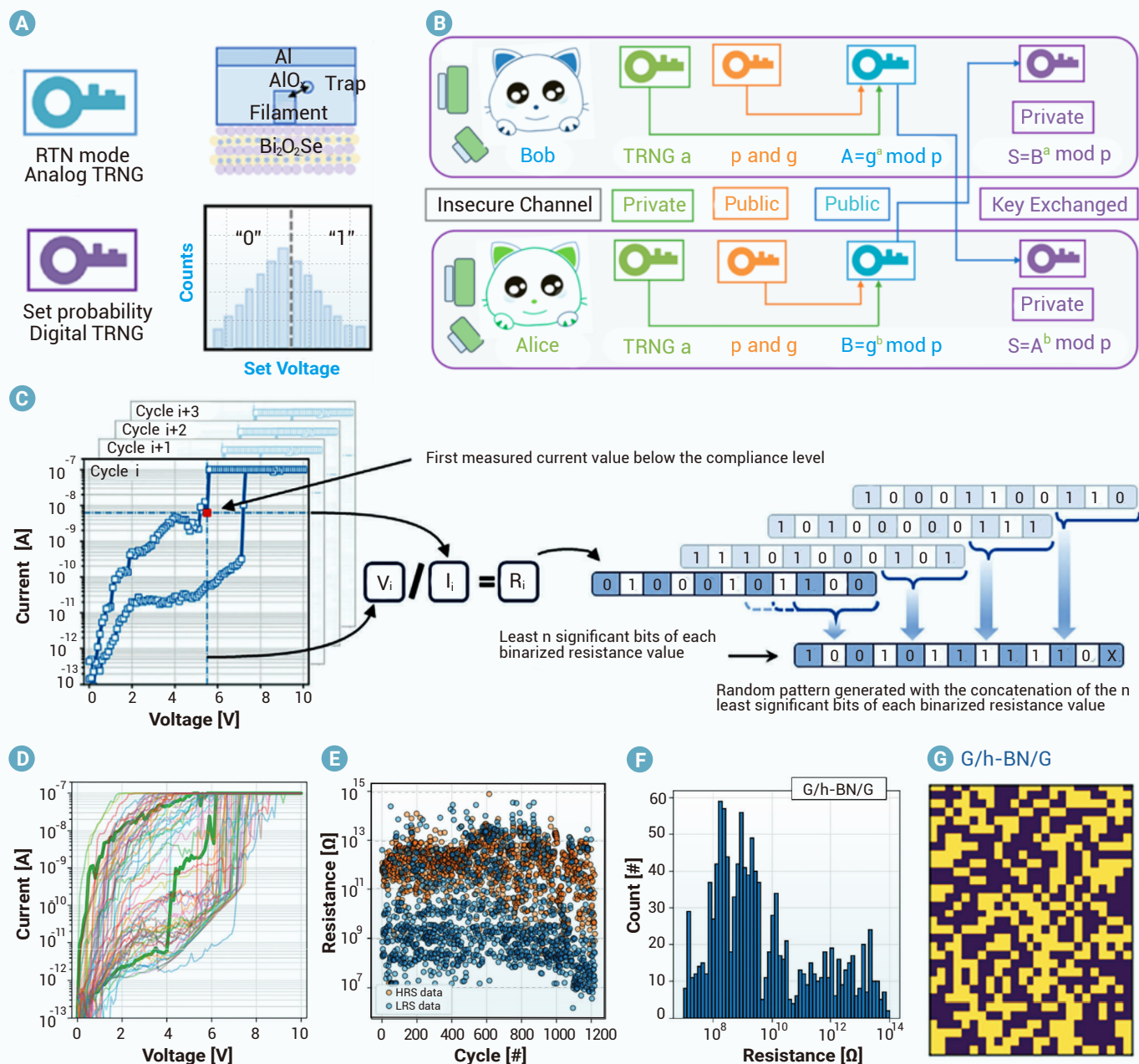


Figure 10. Data encryption based on reconfigurable resistance modulation (A) Schematic diagram of the encryption implementation based on the $\text{Bi}_2\text{O}_2\text{Se}$ with RTN mode and switching probability mode. (B) Diagram of the Diffie-Hellman Key Exchange protocol based on TRNG, in which Bob and Alice successfully exchange a key through an insecure channel. Adapted with permission.²⁸⁹ Copyright 2022, American Chemical Society. (C) Schematic diagram of the working principle of resistance modulation by utilizing the resistance value corresponding to a specific condition during the resistance modulation process. (D–F) Typical I–V plot, resistance-cycle plot of the resistance, and statistical analysis of the resistance in HRS measured in graphene/h-BN/graphene device. (G) The result of the random number sequences generated by the graphene/h-BN/graphene device (arranged as a pattern) in NIST tests, all of which passed. Adapted with permission.²⁹¹ Copyright 2024, Wiley-VCH.

mentation of a neural network, where neuronal and synaptic functions were simulated using volatile and non-volatile devices based on h-BN with Ag and Ti active layers, respectively.²⁸¹ The weight updates of synaptic devices enabled the modulation of the number of firing spikes generated by neuron devices, highlighting the advantages of ion-driven 2D materials-based devices in developing highly integrated artificial neuromorphic systems. Based on their experimental data, the emulation of MNIST handwritten digit image classification achieved a recognition accuracy of 83.45%, comparable to the 90.65% accuracy observed in the ideal case.

Through simulating the parallel information processing capability of biological neural networks, it is feasible to perform more complex image recognition and classification tasks with high accuracy in an energy-efficient manner.^{282,283} Convolutional image processing has been demonstrated to

enable feature extraction from an image using 2D crossbar array differential circuits that perform matrix operations based on Ohm's and Kirchhoff's laws, where the voltage matrix mapped by the pixel matrix is applied to the crossbar array, and the output currents are converted into the processed images.^{90,284,285} Feature extraction from gesture images has been achieved using a Laplacian kernel mapped onto a 3×6 Cu_2S -based crossbar array differential circuit (Figure 9G). The kernel weights (W) were mapped by calculating conductance differences between the average high-resistance state (HRS) and LRS values obtained under different compliance currents (LRS50 for 50 μA and LRS200 for 200 μA) (i.e., $W_1 = G_{\text{HRS}} - G_{\text{HRS}} = 0$, $W_2/W_3 = (G_{\text{LRS200}} - G_{\text{HRS}}) / (G_{\text{HRS}} - G_{\text{LRS50}}) = 4/-1$). The edge features extracted by this hardware convolutional kernel exhibited a high structural similarity index (SSIM) of 0.94 and were tailored for gesture recognition preprocessing (Figure 9H).⁹⁰ The

accuracy of subsequent recognition and classification is expected to be significantly improved, as the subtle features of the image are magnified. These findings highlight the critical role of ion-driven 2D materials-based devices in advancing neuromorphic computing for high-precision information processing, thereby injecting new vitality into the development of reconfigurable intelligent information electronics.

Data encryption

With the rapid development of the IoT, there is an increasing demand for energy-efficient, stable, and miniaturized true random number generator (TRNG) circuits to ensure the secure encryption of massive volumes of sensitive data.²⁸⁶⁻²⁸⁸ Traditional encryption techniques typically rely on complex mathematical algorithms and auxiliary circuits, which are often constrained by high energy consumption and limited scalability, thus hindering their miniaturization and integration. In contrast, ion-driven 2D materials-based devices have emerged as promising candidates for next-generation TRNGs, owing to their ultralow power consumption, atomic-scale thickness,

and intrinsic physical randomness derived from ion transport dynamics. In these devices, the operating voltage and resistance act as natural entropy sources, exhibiting variability due to nanoscale variations in the ion distribution within 2D materials, governed by probabilistic ion hopping over energy barriers. These random variations give rise to measurable electrical signals that can be used to produce truly random binary sequences, which are essential for secure and reliable data encryption in modern electronic systems.

Thanks to their reconfigurable resistance modulation, the intrinsic randomness and tunability of these devices make them ideal candidates for next-generation encryption techniques. For instance, Liu et al. demonstrated a Bi₂O₂Se-based TRNG, where the entropy sources were attributed to random telegraph noise (RTN) signals caused by electron trapping/detrapping near conductive filaments, as well as non-uniform switching voltages (Figures 10A-B).²⁸⁹ This stochastic behavior enabled the encryption of auditory and secure communications, with the inherent randomness ensuring reliable information transmission and supporting cryptographic protocols such as the

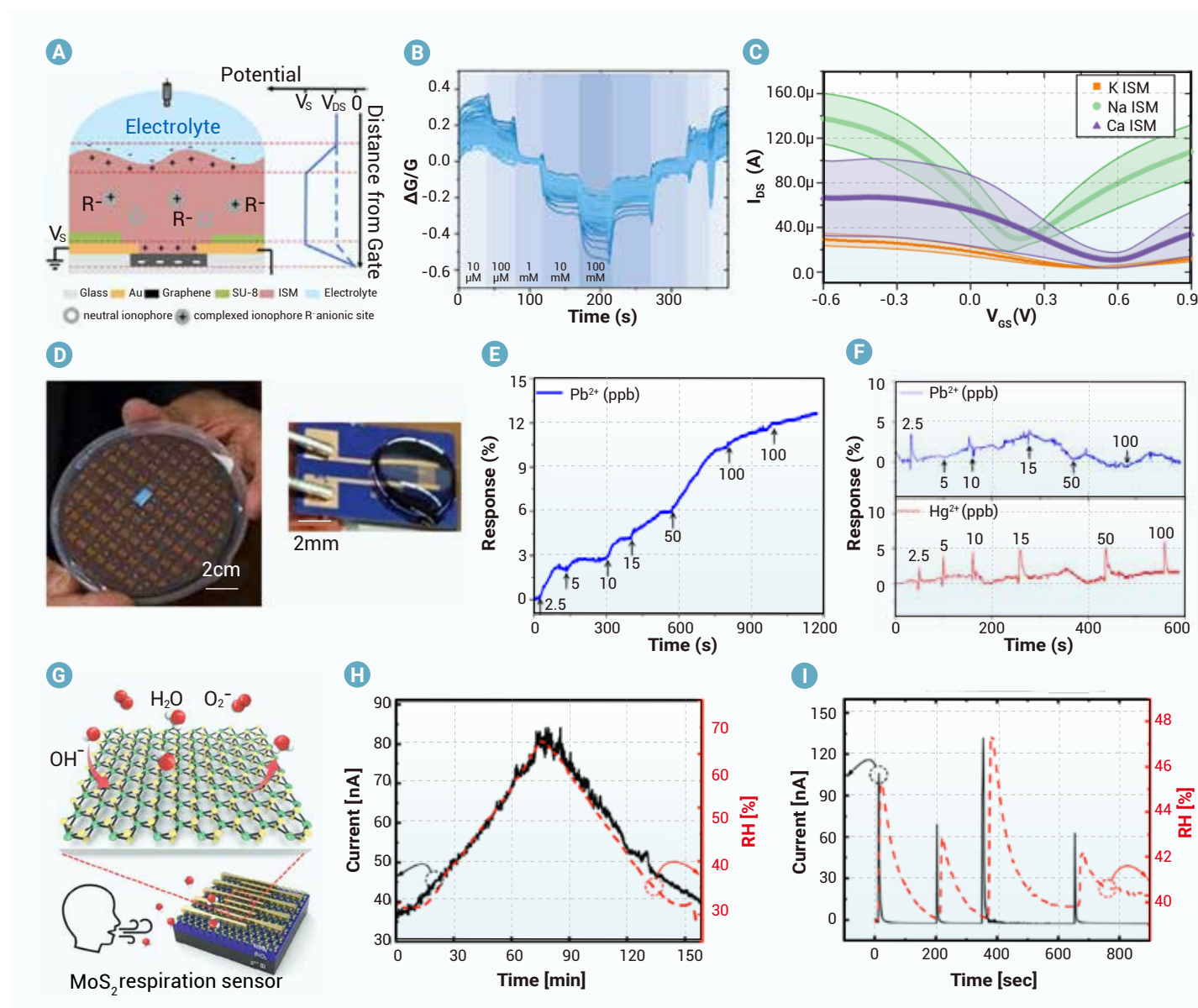


Figure 11. Sensors based on reconfigurable resistance modulation (A) Schematic of the 2D materials-based FET sensor with ion-sensitive surface functionalization membrane. (B) Normalized conductance transient responses of the graphene-based sensors to changing concentrations of Na⁺ ions. (C) The I-V characteristics of the devices in (A), measured in the solution containing K⁺, Na⁺, and Ca²⁺ ions. Adapted with permission.²⁹⁸ Copyright 2022, Springer Nature. (D) Photographs of the wafer-sized graphene-based sensor array for real-time toxins monitoring and a single device with a droplet of test solution on the surface. (E-F) Response transient patterns of the device for single ion (Pb²⁺) and multiple ions (Pb²⁺ and Hg²⁺). Adapted with permission.²⁹⁷ Copyright 2023, Springer Nature. (G) Schematic of the MoS₂-based respiration sensor and its sensing mechanism. (H) Current response of the MoS₂-based sensor in the relative humidity range of 30% to 60%. (I) Current response of the MoS₂-based sensor depending on repeated respiration and comparison with a commercial sensor. Black: MoS₂-based sensor; red: commercial sensor. Adapted with permission.²⁹⁹ Copyright 2025, Wiley-VCH.

Table 1. Multifunctional ion-driven 2D materials-based reconfigurable devices.

Device	Ion species	Resistance change ratio	Switching speed	Number of states	Retention	Energy consumption	Application	Ref.
Au/Ti/h-BN/Au	Ti ³⁺	50	120 ps	2	10 ⁶ s	2 pJ	Ultra-fast memory	69
Graphene/MoS _{2-x} O _x /graphene	O ²⁻	10	100 ns	2	10 ⁵ s	NA	High-temperature storage	70
Ti/h-BN/SiO _x N _y /Si	H ⁺	10 ⁹	NA	3	4×10 ⁴ s	NA	Image storage	302
Ag/In _{4/3} P ₂ S ₆ /graphene	Ag ⁺	10 ⁸	50 ns	278	500 s	1.17 fJ	High-density storage	139
Ag/In _{4/3} P ₂ S ₆ /Au	Ag ⁺	10 ⁹	100 ns	5	10 ⁵ s	18.5 fJ	Logic operations of NIMP, NOT, NAND, NOR, and etc.	267
Dual-gated MoS ₂ transistor	DEME ⁺ , TFSI ⁻	10 ⁵	5.5 ms	20	4 s	12.7 fJ	AND, OR, and NOT logic gates	303
Cr/Au/monolayer-MoS ₂ /Au/Cr	Au	10 ⁵	NA	2	10 ⁴ s	NA	AND and OR logic gates, half adder	304
Ag/WS ₂ /SiO ₂	Na ⁺	10 ⁶	NA	64	10 ⁴ s	1 pJ	Synaptic plasticity (potentiation and depression), image recognition	255
Ag/SnS/Pt	Ag ⁺	10 ⁸	1.5 ns	2	10 ⁵ s	100 fJ	Simulation of synaptic learning behavior	305
Graphene/CuInP ₂ S ₆ /graphene	Cu ⁺	NA	NA	1350	10 ³ s	NA	Simulation of neuronal signal transport ⁸⁴	
Graphene/h-BN/graphene	C, B, N defects	10	100 μs	2	NA	NA	Flexible encryption circuit	291
Ag/h-BN/Pt	Ag ⁺	10	1 ms	3	10 ³ s	NA	True random number generator	292
Ni/h-BN/Au	B vacancy	NA	NA	2	NA	NA	One-time password generator	290
Electrolyte-gated graphene field-effect transistor	Ca ²⁺	NA	5.1 ± 1.1 s	>5	NA	NA	Multi-ion sensor	298
Reduced graphene oxide/thioglycolic acid-Au	Hg ²⁺	NA	10s	>5	NA	NA	Heavy-metal ion sensor	306
Ti/Au/MoS ₂ /Au/Ti	H ⁺ , OH ⁻	2	1 s	>3	NA	NA	Humidity sensor	296

Diffie–Hellman key exchange. Similarly, Wen et al. developed TRNG circuits using RTN signals generated from Ni/h-BN/Au devices to produce one-time passwords for advanced encryption. Their circuits exhibited low power consumption (operating voltage ≈ 0.1V, operating current ≈ 200nA), a high degree of randomness (a long string of 2²⁴ – 1 bits), and a high data throughput of 1Mbit s⁻¹, providing a practical hardware solution for secure communications.²⁹⁰

In addition to RTN, specific resistance values provide another source of intrinsic entropy acquired during resistive switching. The resistance at a user-defined trigger point is determined by the transient ionic configuration, which is inherently unpredictable by conventional algorithms. Han et al. fabricated a TRNG circuit based on a graphene/h-BN/graphene heterostructure, which exhibited significant cycle-to-cycle variations. The resistance value at the first data point during a reverse voltage sweep served as the entropy source.²⁹¹ By extracting the three least significant bits (LSBs) of the binarized resistance from each sweep, the system generated random bitstrings, which functioned as dynamic encryption keys and successfully passed all the National Institute of Standards and Technology (NIST) tests (Figures 10C–G). Meanwhile, the device-to-device variations of the initial resistance and the forming voltage were also exploited as hardware security primitives. Inkjet-printed Ag/h-BN/Pt devices demonstrated considerable randomness in both their initial and post-bias resistance states. The inkjet printing process introduced unpredictable morphology, such as the thickness and orientation of the h-BN films. As a result, it is impossible to predict which devices will be in HRS or LRS within an integrated circuit. This characteristic enables the devices to serve as physical unclonable functions (PUF) for identifying objects or entropy sources. Moreover, the currents of the RTN signals generated by these devices were demonstrated never to exceed the nanoampere regime, ensuring low power consumption while making them highly suitable for energy-efficient security applications in resource-constrained environments.²⁹² These findings demonstrate the flexibility and reliability of leveraging resistance modulation via nanoionics within 2D vdW materials to achieve energy-efficient, highly secure, and miniaturized devices for data encryption, paving a new avenue for the development of advanced information security

technologies.

In addition to the aforementioned applications, ion-driven 2D materials-based devices can also be used for sensor applications.^{293,294} The mechanism stems from the change of carrier density under the influence of the migration and adsorption of ions onto the 2D vdW materials. The adsorption of charged ions causes an increase/decrease in the surface potential, leading to the accumulation of electrons/holes at the surface. Consequently, the Fermi level of the 2D vdW materials shifts towards the conduction band minimum/valence band maximum, resulting in a measurable variation in the device's resistance or current.²⁹⁵ These devices have been demonstrated to classify the ion species, such as Hg²⁺, Pb²⁺, Na⁺, Ca²⁺, and OH⁻ ions, monitoring their concentration at the ppb (cfu/mL) level.^{296–298} For instance, Xue et al. functionalized graphene with different ion-selective membranes (ISM) to fabricate multi-ion sensors. The concentration of target ions (K⁺, Na⁺, and Ca²⁺) was quantitatively detected by monitoring the shift of the Dirac point (the location of the minimum conduction point), demonstrating highly sensitive, reversible, and real-time responses in complex solutions (Figures 11A–C).²⁹⁸ Maity et al. developed a graphene-based FET sensor capable of detecting Pb²⁺ and Hg²⁺ ions both separately and simultaneously in real time (Figures 11D–F).²⁹⁷ Their study provides a reliable quality control protocol to enhance the potential of reconfigurable 2D materials-based sensors for monitoring pollutants in flowing water.

Other 2D vdW materials, such as MoS₂, WS₂, and h-BN, have also emerged as novel materials for sensors.^{299–301} The layered structure of them enables highly efficient ion and charge transfer, endowing the superiority of 2D vdW materials in rapid sensing applications. For instance, Youn et al. reported a MoS₂-based sensor that could monitor humidity changes within the 30% to 60% range relevant to respiration (Figure 11G). At a bias of 5 V, the current increased with rising humidity and decreased with falling humidity (Figure 11H), attributed to OH⁻ ions (generated from water molecule dissociation) adsorbing onto MoS₂ to donate electrons, while proton hopping facilitated charge transport and enhanced conductivity. This device exhibited excellent performance, with a fast response time of 1 s and a recovery time of 3.96 s, significantly faster than commercial sensors (> 200 s) (Figure 11I).²⁹⁶ These stud-

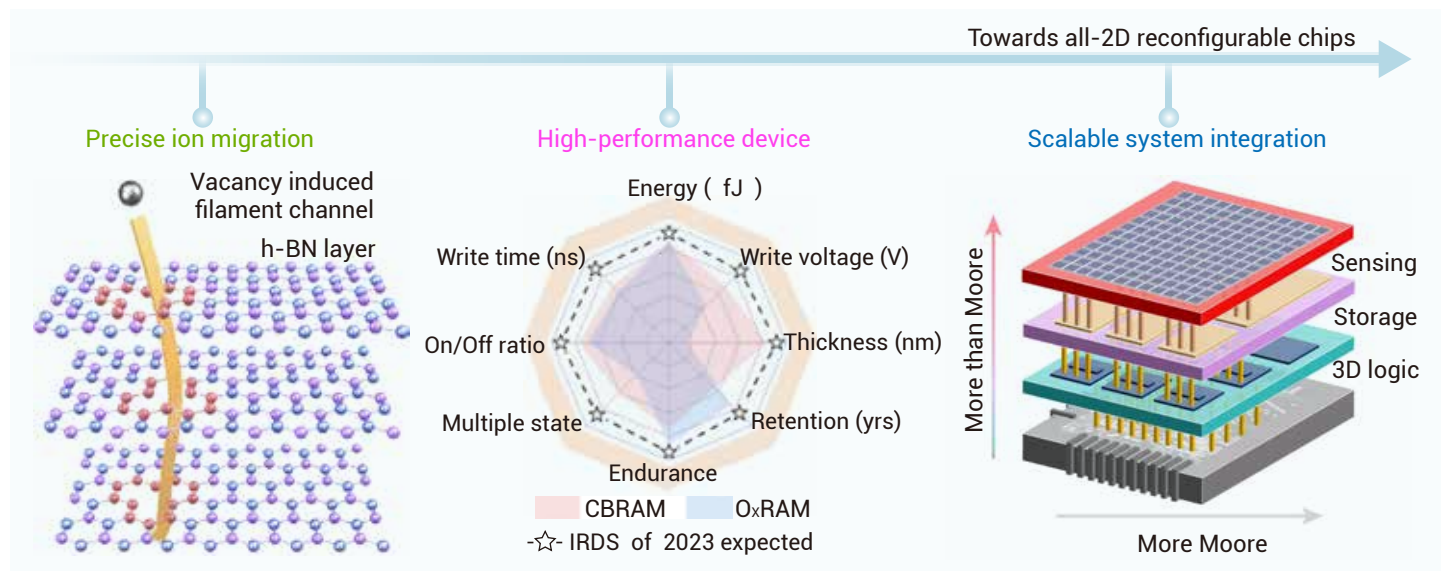


Figure 12. The schematic illustration of perspectives and challenges for ion-driven 2D materials-based devices, including precise ion migration, high device performance, and scalable system integration. Adapted with permission.¹⁴³ Copyright 2025, Elsevier. Adapted with permission.³⁰⁸ Copyright 2024, Springer Nature.

ies open new avenues for the application of ion-driven 2D materials-based devices in advanced sensing and electronic devices.

Recent advances in multifunctional, reconfigurable devices based on ion-driven 2D vdW materials are summarized in Table 1, highlighting key performance metrics relevant to memory, logic, neuromorphic computing, encryption, and sensor applications.

SUMMARY AND OUTLOOK

In this review, we have discussed the reversible modulation of physical properties induced by ion migration in 2D vdW materials, along with recent advancements in ion-driven 2D materials-based reconfigurable devices for information processing. Under an applied electric field, mobile ions (such as Ag^+ , Cu^+ , and Li^+ ions) within 2D vdW materials migrate and redistribute across the layered structure. By precisely controlling this reversible ion migration, it is possible to dynamically modulate the material, including the crystal structure phase, band structure, and interfacial barriers, thereby enabling reconfigurable resistance states in devices. Various strategies were outlined for regulating ion migration, which allow for different resistance modulation modes, including digital switching and analog switching. This tunable functionality empowers ion-driven 2D materials-based reconfigurable devices to perform diverse tasks, such as non-volatile memory, in-memory computing, and hardware-based encryption. Furthermore, the inherent flexibility of these devices shows great promise for the development of miniaturized, multifunctional, and energy-efficient electronics, paving the way for next-generation information technologies.

Despite tremendous progress, several technical challenges must be addressed to transition these devices toward practical applications (Figure 12). The main problems associated with ion-driven 2D materials-based reconfigurable devices are manifested in several aspects.

(1) At the fundamental principle level, the controllability of ion movement in 2D materials-based reconfigurable devices presents formidable challenges. 2D materials, with their unique atomic-scale structures, have emerged as a revolutionary platform. However, precisely controlling ion movement at the atomic scale within these materials remains difficult. The atomic-scale structure of 2D materials creates a complex potential-energy landscape with numerous non-deterministic barriers and channels. Moreover, intrinsic defects in 2D materials can act as ion traps, making it challenging to direct ions along a specific path. These issues also impact the control of the quantity of ions moving in 2D materials, which is crucial for the proper functioning of reconfigurable devices. For example, in a 2D material-based memory device, an excess or deficiency of ions can cause errors in data storage and retrieval. Recent studies suggest that engineering atomic defects, such as nanopores, may enhance the controllability of ion movement.^{143,307} By

precisely controlling the size, shape, and location of these nanopores, it is possible to guide ions along specific paths and selectively allow certain ions to pass through while blocking others, thereby effectively improving the controllability of ion movement.

(2) In performance evaluation, there is a significant shortfall in comprehensively assessing device parameters. Current research landscape is predominantly skewed towards demonstrating single-aspect performance. This narrow focus fails to provide a holistic view of the device's potential for practical applications. The failure to comprehensively evaluate these aspects restricts the practical application of ion-tuned 2D material devices, as a device that excels in one parameter but performs poorly in others may not be suitable for large-scale use. In addition, other vital performance indicators for practical applications have been largely overlooked. Endurance, which is of paramount importance for devices that are frequently used, has rarely undergone systematic research. A device with poor endurance may fail after a limited number of operations, rendering it unreliable for long-term use. Stability under diverse environmental conditions, including temperature and humidity interference is not well studied. These environmental elements can significantly impact the device's performance and reliability. Device production yield is also a critical aspect that has not received due attention. A low production yield means higher costs per device and limited availability, which are major obstacles to the widespread application of ion-driven 2D materials-based reconfigurable devices.

(3) Integrating ion-driven 2D materials-based devices with diverse functionalities shows great potential for advancing high-performance chips. This approach provides a feasible way for 'More than Moore' development, aiming to overcome the traditional limitations of Moore's Law. A practical approach to achieving this integration is to incorporate devices with different functionalities onto the same chip.³⁰⁸ Ensuring compatibility and reliable communication between different functional layers is crucial. However, disparities in mechanical characteristics and communication across different functional layers can give rise to challenges during the integration process. These differences necessitate collaborative optimization.³⁰⁹ The alternative is the all-in-one strategy, where multiple functions are configured within the same device, instead of physically assembling different components. Through a comprehensive understanding of these material attributes, researchers can develop new principles and design methods to enable the co-existence and interaction of multiple functions within a single device. This strategy has the potential to simplify the integration process, reduce the system's size and cost, and enhance its overall performance, making it more suitable for high-performance chip applications.

Looking ahead, nanoion-tuned 2D vdW materials play a crucial role in revolutionizing future reconfigurable nanoelectronics, enabling smaller footprint,

lower energy consumption, and additional functionalities. Devices based on these materials hold great potential for next-generation intelligent information technologies.

REFERENCES

- Pradhan D. K., Moore D. C., Francis A. M., et al. (2024). Materials for high-temperature digital electronics. *Nat. Rev. Mater.* **9**:790–807. DOI:10.1038/s41578-024-00731-9
- Bardeen J. and Brattain W. H. (1948). The transistor, a semi-conductor triode. *Phys. Rev.* **74**:230–231. DOI:10.1103/PhysRev.74.230
- Atalla M. M., Tannenbaum E. and Scheibner E. J. (1959). Stabilization of silicon surfaces by thermally grown oxides. *Bell Syst. Tech. J.* **38**:749–783. DOI:10.1002/j.1538-7305.1959.tb03907.x
- Kilby J. S. (1976). Invention of the integrated circuit. *IEEE Trans. Electron Devices* **23**:648–654. DOI:10.1109/T-ED.1976.18467
- Chang L., Yang-kyu C., Ha D., et al. (2003). Extremely scaled silicon nano-CMOS devices. *Proc. IEEE* **91**:1860–1873. DOI:10.1109/JPROC.2003.818336
- Davari B., Dennard R. H. and Shahidi G. G. (1995). CMOS scaling for high performance and low power—the next ten years. *Proc. IEEE* **83**:595–606. DOI:10.1109/5.371968
- Cheng Z., Pang C.-S., Wang P., et al. (2022). How to report and benchmark emerging field-effect transistors. *Nat. Electron.* **5**:416–423. DOI:10.1038/s41928-022-00798-8
- Syu J. H., Lin J. C. W., Srivastava G., et al. (2023). A comprehensive survey on artificial intelligence empowered edge computing on consumer electronics. *IEEE Trans. Consum. Electron.* **69**:1023–1034. DOI:10.1109/TCE.2023.3318150
- Hua H., Li Y., Wang T., et al. (2023). Edge computing with artificial intelligence: A machine learning perspective. *ACM Comput. Surv.* **55**:Article 184. DOI:10.1145/3555802
- Tsai C. W., Lai C. F., Chiang M. C., et al. (2014). Data mining for internet of things: A survey. *IEEE Commun. Surv. Tutorials* **16**:77–97. DOI:10.1109/SURV.2013.103013.00206
- Mikolajick T., Heinzig A., Trommer J., et al. (2017). The RFET—a reconfigurable nanowire transistor and its application to novel electronic circuits and systems. *Semicond. Sci. Technol.* **32**:043001. DOI:10.1088/1361-6641/aa5581
- Weber W. M., Heinzig A., Trommer J., et al. (2014). Reconfigurable nanowire electronics – A review. *Solid-State Electron.* **102**:12–24. DOI:10.1016/j.sse.2014.06.010
- Zhu Z., Ng D. W. H., Park H. S., et al. (2021). 3D-printed multifunctional materials enabled by artificial-intelligence-assisted fabrication technologies. *Nat. Rev. Mater.* **6**:27–47. DOI:10.1038/s41578-020-00235-2
- Rai S., Trommer J., Raitza M., et al. (2019). Designing efficient circuits based on runtime-reconfigurable field-effect transistors. *IEEE Trans. Very Large Scale Integr. VLSI Syst.* **27**:560–572. DOI:10.1109/TVLSI.2018.2884646
- Qiu E., Zhang Y.-H., Ventra M. D., et al. (2024). Reconfigurable cascaded thermal neuristors for neuromorphic computing. *Adv. Mater.* **36**:2306818. DOI:10.1002/adma.202306818
- Zhu J., Dexheimer M. and Cheng H. (2017). Reconfigurable systems for multifunctional electronics. *npj Flex. Electron.* **1**:8. DOI:10.1038/s41528-017-0009-6
- Chen C. K., Hooda S., Fang Z., et al. (2023). High-performance top-gated and double-gated oxide–semiconductor ferroelectric field-effect transistor enabled by channel defect self-compensation effect. *IEEE Trans. Electron Devices* **70**:2098–2105. DOI:10.1109/TED.2023.3242633
- Lundstrom M. (2003). Moore's law forever. *Science* **299**:210–211. DOI:10.1126/science.1079567
- Zidan M. A., Strachan J. P. and Lu W. D. (2018). The future of electronics based on memristive systems. *Nat. Electron.* **1**:22–29. DOI:10.1038/s41928-017-0006-8
- Tan C., Tang J., Gao X., et al. (2025). 2D bismuth oxyselenide semiconductor for future electronics. *Nat. Rev. Electr. Eng.* **2**:494–513. DOI:10.1038/s44287-025-00179-1
- Ataca C., Şahin H. and Ciraci S. (2012). Stable, single-layer MX₂ transition-metal oxides and dichalcogenides in a honeycomb-like structure. *J. Phys. Chem. C* **116**:8983–8999. DOI:10.1021/jp212558p
- Pang J., Zhang S., Rummeli M. H., et al. (2023). Evolving MXene species. *Innov. Mater.* **1**:100027. DOI:10.59717/j.xinn-mater.2023.100027
- Huh W., Lee D. and Lee C.-H. (2020). Memristors based on 2D materials as an artificial synapse for neuromorphic electronics. *Adv. Mater.* **32**:2002092. DOI:10.1002/adma.202002092
- Kim K., Choi J.-Y., Kim T., et al. (2011). A role for graphene in silicon-based semiconductor devices. *Nature* **479**:338–344. DOI:10.1038/nature10680
- Zou X., Xu Y. and Duan W. (2021). 2D materials: Rising star for future applications. *The Innovation* **2**. DOI:10.1016/j.xinn.2021.100115
- Serles P., Arif T., Puthirath A. B., et al. Friction of magnetene, a non–van der Waals 2D material. *Sci. Adv.* **7**:eabk2041. DOI:10.1126/sciadv.abk2041
- Turunen M., Brotons-Gisbert M., Dai Y., et al. (2022). Quantum photonics with layered 2D materials. *Nat. Rev. Phys.* **4**:219–236. DOI:10.1038/s42254-021-00408-0
- Favron A., Gaufres E., Fossard F., et al. (2015). Photooxidation and quantum confinement effects in exfoliated black phosphorus. *Nat. Mater.* **14**:826–832. DOI:10.1038/nmat4299
- Nakamura K., Nagamura N., Ueno K., et al. (2020). All 2D heterostructure tunnel field-effect transistors: Impact of band alignment and heterointerface quality. *ACS Appl. Mater. Interfaces* **12**:51598–51606. DOI:10.1021/acsami.0c13233
- Ben Jabra Z., Abel M., Fabbri F., et al. (2022). Van der Waals heteroepitaxy of air-stable quasi-free-standing silicene layers on CVD epitaxial graphene/6H-SiC. *ACS Nano* **16**:5920–5931. DOI:10.1021/acsnano.1c11122
- Diallo T. M., Hanuš T., Patriarche G., et al. (2024). Unraveling the heterointegration of 3D semiconductors on graphene by anchor point nucleation. *Small* **20**:2306038. DOI:10.1002/sml.202306038
- Liu Y., Duan X., Huang Y., et al. (2018). Two-dimensional transistors beyond graphene and TMDCs. *Chem. Soc. Rev.* **47**:6388–6409. DOI:10.1039/C8CS00318A
- Ng H. K., Xiang D., Suwardi A., et al. (2022). Improving carrier mobility in two-dimensional semiconductors with rippled materials. *Nat. Electron.* **5**:489–496. DOI:10.1038/s41928-022-00777-z
- Zeng S., Liu C. and Zhou P. (2024). Transistor engineering based on 2D materials in the post-silicon era. *Nat. Rev. Electr. Eng.* **1**:335–348. DOI:10.1038/s44287-024-00045-6
- Butler S. Z., Hollen S. M., Cao L., et al. (2013). Progress, challenges, and opportunities in two-dimensional materials beyond graphene. *ACS Nano* **7**:2898–2926. DOI:10.1021/nn400280c
- Xie L., Liao M., Wang S., et al. (2017). Graphene-contacted ultrashort channel monolayer MoS₂ transistors. *Adv. Mater.* **29**:1702522. DOI:10.1002/adma.201702522
- Cheng Z., Backman J., Zhang H., et al. (2023). Distinct contact scaling effects in MoS₂ transistors revealed with asymmetrical contact measurements. *Adv. Mater.* **35**:2210916. DOI:10.1002/adma.202210916
- Zhao W., Ghorannevis Z., Chu L., et al. (2013). Evolution of electronic structure in atomically thin sheets of WS₂ and WSe₂. *ACS Nano* **7**:791–797. DOI:10.1021/nn305275h
- Li L., Deng Q., Sun Y., et al. (2023). 2D short-channel tunneling transistor relying on dual-gate modulation for integrated circuits application. *Adv. Funct. Mater.* **33**:2304591. DOI:10.1002/adfm.202304591
- Deng Q., Zhao T., Zhang J., et al. (2024). Reconfigurable vertical phototransistor with MoTe₂ homojunction for high-speed rectifier and multivalued logical circuits. *ACS Nano* **18**:23702–23710. DOI:10.1021/acsnano.4c08345
- Zhu Y., Long R. and Fang W.-H. (2023). Substrate ferroelectric proximity effects have a strong influence on charge carrier lifetime in black phosphorus. *Nano Lett.* **23**:10074–10080. DOI:10.1021/acs.nanolett.3c03570
- Nangung S., Koester S. J. and Oh S.-H. (2021). Ultrafast sub-10 nanometer gap electrodes for two-dimensional optoelectronic devices. *ACS Nano* **15**:5276–5283. DOI:10.1021/acsnano.0c10759
- Bandurin D. A., Tyurnina A. V., Yu G. L., et al. (2017). High electron mobility, quantum Hall effect and anomalous optical response in atomically thin InSe. *Nat. Nanotechnol.* **12**:223–227. DOI:10.1038/nnano.2016.242
- Xiang Y., Wang C., Liu C., et al. (2025). Subnanosecond flash memory enabled by 2D-enhanced hot-carrier injection. *Nature* **641**:90–97. DOI:10.1038/s41586-025-08839-w
- Wang Z., Liu X., Zhou X., et al. (2022). Reconfigurable quasi-nonvolatile memory/subthermionic FET functions in ferroelectric–2D semiconductor vdW architectures. *Adv. Mater.* **34**:2200032. DOI:10.1002/adma.202200032
- Yang J. Y., Park M., Yeom M. J., et al. (2023). Reconfigurable physical reservoir in GaN/α-In₂Se₃ HEMTs enabled by out-of-plane local polarization of ferroelectric 2D layer. *ACS Nano* **17**:7695–7704. DOI:10.1021/acsnano.3c00187
- Li C., Tian R., Chen X., et al. (2022). Waveguide-integrated MoTe₂ p–i–n homojunction photodetector. *ACS Nano* **16**:20946–20955. DOI:10.1021/acsnano.2c08549
- Wang P., Mu H., Yun T., et al. (2025). High rectification and gate-tunable photoresponse in 1D–2D lateral van der Waals heterojunctions. *Innov. Mater.* **3**:100113. DOI:10.59717/j.xinn-mater.2024.100113
- Jiang J., Xu L., Qiu C., et al. (2023). Ballistic two-dimensional InSe transistors. *Nature* **616**:470–475. DOI:10.1038/s41586-023-05819-w
- Tan C., Yu M., Tang J., et al. (2023). 2D fin field-effect transistors integrated with epitaxial high-k gate oxide. *Nature* **616**:66–72. DOI:10.1038/s41586-023-05797-z
- Fei W., Trommer J., Lemme M. C., et al. (2022). Emerging reconfigurable electronic devices based on two-dimensional materials: A review. *InfoMat* **4**:e12355. DOI:10.1002/inf2.12355
- Zhang J., Liu W., Dai J., et al. (2022). Nanoionics from biological to artificial systems: An alternative beyond nanoelectronics. *Adv. Sci.* **9**:2200534. DOI:10.1002/adv.202200534
- Yang Y., Wang M., He Q., et al. (2025). Ion transport behavior in van der Waals Gaps of 2D materials. *Small* **21**:2310681. DOI:10.1002/sml.202310681
- Liao K., Chen L., Meng R., et al. (2024). Reconstructable carbon monolayer–MoS₂ intercalated heterostructure enabled by atomic layers-confined topotactic transformation for ultrafast lithium storage. *J. Am. Chem. Soc.* **146**:12020–12029. DOI:10.1021/jacs.4c01550
- Shi W., Kahn S., Jiang L., et al. (2020). Reversible writing of high-mobility and high-carrier-density doping patterns in two-dimensional van der Waals heterostructures.

- Nat. Electron.* **3**:99–105. DOI:10.1038/s41928-019-0351-x
56. Kim T., Won J., Bae J., et al. (2025). Memristive InAs-based semiconductors with anisotropic ion transport. *Adv. Mater.* **37**:2500056. DOI:10.1002/adma.202500056
 57. Muscher P. K., Rehn D. A., Sood A., et al. (2021). Highly efficient uniaxial in-plane stretching of a 2D material via ion insertion. *Adv. Mater.* **33**:2101875. DOI:10.1002/adma.202101875
 58. Park H., Lee M., Wang X., et al. (2024). Anisotropic charge transport at the metallic edge contact of ReS₂ field effect transistors. *Commun. Mater.* **5**:87. DOI:10.1038/s43246-024-00526-z
 59. Sun P., Ma R. and Sasaki T. (2018). Recent progress on exploring exceptionally high and anisotropic H⁺/OH⁻ ion conduction in two-dimensional materials. *Chem. Sci.* **9**:33–43. DOI:10.1039/C7SC04019A
 60. Ram A., Maity K., Marchand C., et al. (2023). Reconfigurable multifunctional van der Waals ferroelectric devices and logic circuits. *ACS Nano* **17**:21865–21877. DOI:10.1021/acsnano.3c07952
 61. Uzhansky M., Mukherjee S., Vijayan G., et al. (2024). Non-volatile reconfigurable p–n junction utilizing in-plane ferroelectricity in 2D WSe₂/α-In₂Se₃ asymmetric heterostructures. *Adv. Funct. Mater.* **34**:2306682. DOI:10.1002/adfm.202306682
 62. Mei T., Chen F., Huang T., et al. (2025). Ion–electron interactions in 2D nanomaterials-based artificial synapses for neuromorphic applications. *ACS Nano* **19**:17140–17172. DOI:10.1021/acsnano.5c02397
 63. Yang Q., Li X., Zhao L., et al. (2025). Unified transmission electron microscopy with the glovebox integrated system for investigating air-sensitive two-dimensional quantum materials. *The Innovation* **6**:100751. DOI:10.1016/j.xinn.2024.100751
 64. Li W., Qian X. and Li J. (2021). Phase transitions in 2D materials. *Nat. Rev. Mater.* **6**:829–846. DOI:10.1038/s41578-021-00304-0
 65. Nirmal K. A., Kumbhar D. D., Kesavan A. V., et al. (2024). Advancements in 2D layered material memristors: Unleashing their potential beyond memory. *npj 2D Mater. Appl.* **8**:83. DOI:10.1038/s41699-024-00522-4
 66. Jiang J., Xu T., Lu J., et al. Defect engineering in 2D materials: Precise manipulation and improved functionalities. *Research* **2019**. DOI:10.34133/2019/4641739
 67. Papadopoulos S., Agarwal T., Jain A., et al. (2022). Ion migration in monolayer MoS₂ memristors. *Phys. Rev. Appl.* **18**:014018. DOI:10.1103/PhysRevApplied.18.014018
 68. Ghorbani-Asl M., Kretschmer S., Spearot D. E., et al. (2017). Two-dimensional MoS₂ under ion irradiation: From controlled defect production to electronic structure engineering. *2D Mater.* **4**:025078. DOI:10.1088/2053-1583/aa6b17
 69. Teja Nibhanupudi S. S., Roy A., Veksler D., et al. (2024). Ultra-fast switching memristors based on two-dimensional materials. *Nat. Commun.* **15**:2334. DOI:10.1038/s41467-024-46372-y
 70. Wang M., Cai S., Pan C., et al. (2018). Robust memristors based on layered two-dimensional materials. *Nat. Electron.* **1**:130–136. DOI:10.1038/s41928-018-0021-4
 71. Chen S., Mahmoodi M. R., Shi Y., et al. (2020). Wafer-scale integration of two-dimensional materials in high-density memristive crossbar arrays for artificial neural networks. *Nat. Electron.* **3**:638–645. DOI:10.1038/s41928-020-00473-w
 72. Lee G. S., Kim J. G., Kim J. T., et al. (2024). 2D materials beyond post-AI era: Smart fibers, soft robotics, and single atom catalysts. *Adv. Mater.* **36**:2307689. DOI:10.1002/adma.202307689
 73. Pomerantseva E. and Gogotsi Y. (2017). Two-dimensional heterostructures for energy storage. *Nat. Energy* **2**:17089. DOI:10.1038/nenergy.2017.89
 74. Shifa T. A., Wang F., Liu Y., et al. (2019). Heterostructures based on 2D materials: A versatile platform for efficient catalysis. *Adv. Mater.* **31**:1804828. DOI:10.1002/adma.201804828
 75. Zhou F., Chen J., Tao X., et al. 2D materials based optoelectronic memory: Convergence of electronic memory and optical sensor. *Research* **2019**. DOI:10.34133/2019/9490413
 76. Ci W., Wang P., Xue W., et al. (2024). Engineering ferroelectric/ion-modulated conductance in 2D vdW CuInP₂S₆ for non-volatile digital memory and artificial synapse. *Adv. Funct. Mater.* **34**:2316360. DOI:10.1002/adfm.202316360
 77. Chen J., Zhu C., Cao G., et al. (2022). Mimicking neuroplasticity via ion migration in van der Waals layered copper indium thiophosphate. *Adv. Mater.* **34**:2104676. DOI:10.1002/adma.202104676
 78. Lee M. J., Kim S.-H., Lee S., et al. (2020). Understanding filamentary growth and rupture by Ag ion migration through single-crystalline 2D layered CrPS₄. *NPG Asia Mater.* **12**:82. DOI:10.1038/s41427-020-00272-x
 79. Zabelotsky T., Singh S., Haim G., et al. (2023). Creation of boron vacancies in hexagonal boron nitride exfoliated from bulk crystals for quantum sensing. *ACS Appl. Nano Mater.* **6**:21671–21678. DOI:10.1021/acsnanm.3c03395
 80. Kang C., Choi H., Son H., et al. (2023). A steep-switching impact ionization-based threshold switching field-effect transistor. *Nanoscale* **15**:5771–5777. DOI:10.1039/D2NR06547A
 81. Marques-Moros F., Boix-Constant C., Mañas-Valero S., et al. (2023). Interplay between optical emission and magnetism in the van der Waals magnetic semiconductor CrSBr in the two-dimensional limit. *ACS Nano* **17**:13224–13231. DOI:10.1021/acsnano.3c00375
 82. Ma M. Y., Chen N. K., Wang D., et al. (2023). Defect physics in 2D monolayer I-VII semiconductor AgI. *Mater. Today Nano* **22**:100304. DOI:10.1016/j.mtnano.2023.100304
 83. Jiang X., Zhang X., Deng Z., et al. (2024). Dual-role ion dynamics in ferroionic CuInP₂S₆: Revealing the transition from ferroelectric to ionic switching mechanisms. *Nat. Commun.* **15**:10822. DOI:10.1038/s41467-024-55160-7
 84. Sun Y., Zhang R., Teng C., et al. (2023). Internal ion transport in ionic 2D CuInP₂S₆ enabling multi-state neuromorphic computing with low operation current. *Mater. Today* **66**:9–16. DOI:10.1016/j.mattod.2023.04.013
 85. Guo C., Zhu J., Liang X., et al. (2024). Atomic-level direct imaging for Cu(I) multiple occupations and migration in 2D ferroelectric CuInP₂S₆. *Nat. Commun.* **15**:10152. DOI:10.1038/s41467-024-54229-7
 86. Malik A. M., Albe K. and Rohrer J. (2025). Vacancy formation energy as a descriptor of the exfoliability of MAX phases to MXenes. *npj 2D Mater. Appl.* **9**:56. DOI:10.1038/s41699-025-00581-1
 87. Li Z. and Chen F. (2017). Ion beam modification of two-dimensional materials: Characterization, properties, and applications. *Appl. Phys. Rev.* **4**:011103. DOI:10.1063/1.4977087
 88. Qi Y., Sadi M. A., Hu D., et al. (2023). Recent progress in strain engineering on van der Waals 2D materials: Tunable electrical, electrochemical, magnetic, and optical properties. *Adv. Mater.* **35**:2205714. DOI:10.1002/adma.202205714
 89. Du S., Yang W., Gao H., et al. (2024). Sliding memristor in parallel-stacked hexagonal boron nitride. *Adv. Mater.* **36**:2404177. DOI:10.1002/adma.202404177
 90. Qin L., Yu Y., Fang C., et al. (2025). Intrinsic ion migration-induced susceptible two-dimensional phase-transition memristor with ultralow power consumption. *Sci. Bull.* **70**:2116–2124. DOI:10.1016/j.scib.2025.03.051
 91. Chen W., Wang Z., Bets K. V., et al. (2021). Millisecond conversion of metastable 2D materials by flash Joule heating. *ACS Nano* **15**:1282–1290. DOI:10.1021/acsnano.0c08460
 92. Yang S.-Z., Sun W., Zhang Y.-Y., et al. (2019). Direct cation exchange in monolayer MoS₂ via recombination-enhanced migration. *Phys. Rev. Lett.* **122**:106101. DOI:10.1103/PhysRevLett.122.106101
 93. Yang X., Luo Y., Li J., et al. (2022). Tuning mixed electronic/ionic conductivity of 2D CdPS₃ nanosheets as an anode material by synergistic intercalation and vacancy engineering. *Adv. Funct. Mater.* **32**:2112169. DOI:10.1002/adfm.202112169
 94. Zheng J., Zhang H., Dong S., et al. (2014). High yield exfoliation of two-dimensional chalcogenides using sodium naphthalenide. *Nat. Commun.* **5**:2995. DOI:10.1038/ncomms3995
 95. Li J., Ge X., Liang Q., et al. (2024). Quantitative pre-intercalation of alkali metal ions enables precisely modulating Li⁺ storage of MXenes. *Energy Storage Mater.* **73**:103828. DOI:10.1016/j.ensm.2024.103828
 96. Zhao Y., Chen D., Deng Z., et al. (2025). Stacking-dependent ion adsorption and diffusion in Janus MoSSe bilayers: Insights for battery applications. *J. Power Sources* **641**:236855. DOI:10.1016/j.jpowsour.2025.236855
 97. Zhang H., Koledin T. D., Wang X., et al. (2022). Stabilizing the heavily-doped and metallic phase of MoS₂ monolayers with surface functionalization. *2D Mater.* **9**:015033. DOI:10.1088/2053-1583/ac3f44
 98. Stephenson T., Li Z., Olsen B., et al. (2014). Lithium ion battery applications of molybdenum disulfide (MoS₂) nanocomposites. *Energy Environ. Sci.* **7**:209–231. DOI:10.1039/C3EE42591F
 99. Zhu Q., Li W., Wu J., et al. (2022). Vacancy engineering in WS₂ nanosheets for enhanced potassium - ion storage. *J. Power Sources* **542**:231791. DOI:10.1016/j.jpowsour.2022.231791
 100. Luo X., Huang J., Cao L., et al. (2023). Constructing multi-dimensional migration channel by nickel-doped WS₂ composite: High speed sodium and potassium ion storage kinetics in WS₂ nanosheets. *Chem. Eng. J.* **464**:142579. DOI:10.1016/j.ccej.2023.142579
 101. Yang R., Mei L., Lin Z., et al. (2024). Intercalation in 2D materials and in situ studies. *Nat. Rev. Chem.* **8**:410–432. DOI:10.1038/s41570-024-00605-2
 102. Chen Q., Wei Y., Zhai P.-B., et al. (2024). Van der Waals gap engineering in 2D materials for energy storage and conversion. *Rare Met.* **43**:6125–6143. DOI:10.1007/s12598-024-02817-3
 103. Ghosh K., Ng S., Lazar P., et al. (2024). 2D germanane-MXene heterostructures for cations intercalation in energy storage applications. *Adv. Funct. Mater.* **34**:2308793. DOI:10.1002/adfm.202308793
 104. Fernandes J., Grzonka J., Araújo G., et al. (2024). Bipolar resistive switching in 2D MoSe₂ grown by atmospheric pressure chemical vapor deposition. *ACS Appl. Mater. Interfaces* **16**:1767–1778. DOI:10.1021/acsaami.3c14215
 105. Xu R., Jiang H., Lee M.-H., et al. (2019). Vertical MoS₂ double-layer memristor with electrochemical metallization as an atomic-scale synapse with switching thresholds approaching 100 mV. *Nano Lett.* **19**:2411–2417. DOI:10.1021/acs.nanolett.8b05140
 106. Khot A. C., Dongale T. D., Nirmal K. A., et al. (2022). Amorphous boron nitride memristive device for high-density memory and neuromorphic computing applications. *ACS Appl. Mater. Interfaces* **14**:10546–10557. DOI:10.1021/acsaami.1c23268
 107. Yin S., Luo Z., Li Q., et al. (2019). Emulation of learning and memory behaviors by memristor based on Ag migration on 2D MoS₂ surface. *Phys. Status Solidi A* **216**:1900104. DOI:10.1002/pssa.201900104
 108. Li C., Xu T., Pan R., et al. (2024). Electric field-dependent evolution dynamics of conductive filaments in 2D material-based planar memristors. *ACS Nano* **18**:32196–32204. DOI:10.1021/acsnano.4c11598
 109. Mitra S. and Mahapatra S. (2024). Atomistic description of conductive bridge

- formation in two-dimensional material based memristor. *npj 2D Mater. Appl.* **8**:26. DOI:10.1038/s41699-024-00465-w
110. Boland M. J., Sundararajan A., Farrokhi M. J., et al. (2016). Nonlinear ballistic transport in an atomically thin material. *ACS Nano* **10**:1231–1239. DOI:10.1021/acsnano.5b06546
111. Lee C. H., Park Y., Youn S., et al. (2022). Design of p-WSe₂/n-Ge heterojunctions for high-speed broadband photodetectors. *Adv. Funct. Mater.* **32**:2107992. DOI:10.1002/adfm.202107992
112. Zhou Y., Zhang C., Huang D., et al. (2022). Structure defined 2D Mo₂C/2Dg-C₃N₄ van der Waals heterojunction: Oriented charge flow in-plane and separation within the interface to collectively promote photocatalytic degradation of pharmaceutical and personal care products. *Appl. Catal., B* **301**:120749. DOI:10.1016/j.apcatb.2021.120749
113. Waser R., Dittmann R., Staikov G., et al. (2009). Redox-based resistive switching memories – nanoionic mechanisms, prospects, and challenges. *Adv. Mater.* **21**:2632–2663. DOI:10.1002/adma.200900375
114. Waser R. and Aono M. (2007). Nanoionics-based resistive switching memories. *Nat. Mater.* **6**:833–840. DOI:10.1038/nmat2023
115. Han S. S., Shawkat M. S., Lee Y. H., et al. (2022). Wafer-scale anion exchange conversion of nonlayered PTS films to van der Waals two-dimensional PtTe₂ layers with negative photoresponsiveness. *Chem. Mater.* **34**:6996–7005. DOI:10.1021/acs.chemmater.2c01452
116. Du L., Hasan T., Castellanos-Gomez A., et al. (2021). Engineering symmetry breaking in 2D layered materials. *Nat. Rev. Phys.* **3**:193–206. DOI:10.1038/s42254-020-00276-0
117. Xiao Y., Zhou M., Zeng M., et al. (2019). Atomic-scale structural modification of 2D materials. *Adv. Sci.* **6**:1801501. DOI:10.1002/advs.201801501
118. Kim S., Cui J., Dravid V. P., et al. (2019). Orientation-dependent intercalation channels for lithium and sodium in black phosphorus. *Adv. Mater.* **31**:1904623. DOI:10.1002/adma.201904623
119. Xiang P., Chen X., Zhang W., et al. (2017). Metallic borophene polytypes as lightweight anode materials for non-lithium-ion batteries. *Phys. Chem. Chem. Phys.* **19**:24945–24954. DOI:10.1039/C7CP04989G
120. Ueda A., Zhang Y., Sano N., et al. (2020). Ambipolar device simulation based on the drift-diffusion model in ion-gated transition metal dichalcogenide transistors. *npj Comput. Mater.* **6**:24. DOI:10.1038/s41524-020-0293-x
121. Xu X., Chen Y., Liu P., et al. (2024). General synthesis of ionic-electronic coupled two-dimensional materials. *Nat. Commun.* **15**:4368. DOI:10.1038/s41467-024-48690-7
122. Ge R., Wu X., Liang L., et al. (2021). A library of atomically thin 2D materials featuring the conductive-point resistive switching phenomenon. *Adv. Mater.* **33**:2007792. DOI:10.1002/adma.202007792
123. Zhu H., Li J., Chen Q., et al. (2023). Highly tunable lateral homojunction formed in two-dimensional layered CuInP₂S₆ via in-plane ionic migration. *ACS Nano* **17**:1239–1246. DOI:10.1021/acsnano.2c09280
124. Ni S., Jiang J., Wang W., et al. (2025). Beryllium dinitride monolayer: A multifunctional direct bandgap anisotropic semiconductor containing polymeric nitrogen with oxygen reduction catalysis and potassium-ion storage capability. *J. Mater. Chem. A* **13**:10214–10223. DOI:10.1039/D4TA08565E
125. Sun Y., Zhang R., Tan J., et al. Tunable in-plane conductance anisotropy in 2D semiconductive AgCrP₂S₆ by ion-electron co-modulations. *Sci. Adv.* **11**:eadr3105. DOI:10.1126/sciadv.adr3105
126. Liu H., Zhang Y., Glukhova O. E., et al. (2022). Interlayer hopping kinetics of vacancies in CrI₃ layers leading to monolayer/bilayer heterostructures. *Adv. Mater. Interfaces* **9**:2200626. DOI:10.1002/admi.202200626
127. Shen T., Li F., Xu L., et al. (2020). High mobility monolayer MoS₂ transistors and its charge transport behaviour under E-beam irradiation. *J. Mater. Sci.* **55**:14315–14325. DOI:10.1007/s10853-020-04977-w
128. Olsson E., Hussain T., Kartan A., et al. (2020). The adsorption and migration behavior of divalent metals (Mg, Ca, and Zn) on pristine and defective graphene. *Carbon* **163**:276–287. DOI:10.1016/j.carbon.2020.03.028
129. Wang Z., Chen J., Cao Z., et al. (2025). First-principles study of anionic diffusion in two-dimensional lead halide perovskite lateral heterostructures. *ACS Appl. Mater. Interfaces* **17**:7019–7026. DOI:10.1021/acsam.1c01155
130. Sangwan V. K., Jariwala D., Kim I. S., et al. (2015). Gate-tunable memristive phenomena mediated by grain boundaries in single-layer MoS₂. *Nat. Nanotechnol.* **10**:403–406. DOI:10.1038/nnano.2015.56
131. Lee D. J., Lee Y., Hong C.-W., et al. (2021). Liquid-to-solid exfoliated Ag/2D-SnO/Au flexible memristor with electric field direction-dependent asymmetric hysteresis characteristics. *J. Mater. Res. Technol.* **15**:3538–3546. DOI:10.1016/j.jmrt.2021.09.147
132. Wu H., Guo Z., Zhou J., et al. (2019). Vacancy-mediated lithium adsorption and diffusion on MXene. *Appl. Surf. Sci.* **488**:578–585. DOI:10.1016/j.apsusc.2019.05.311
133. Wang G., Luo X., Chen C., et al. (2023). Defect-engineered hexagonal boron nitride nanosheets as a new atomic-level directional ion conductor. *Ceram. Int.* **49**:23391–23398. DOI:10.1016/j.ceramint.2023.04.171
134. Yoo J., Nam C.-Y. and Bussmann E. (2024). Atomic precision processing of two-dimensional materials for next-generation microelectronics. *ACS Nano* **18**:21614–21622. DOI:10.1021/acsnano.4c04908
135. Zhang H. (2018). Introduction: 2D materials chemistry. *Chem. Rev.* **118**:6089–6090. DOI:10.1021/acs.chemrev.8b00278
136. Pushkarev G. V., Mazurenko V. G., Mazurenko V. V., et al. (2023). Nature of interlayer bonds in two-dimensional materials. *J. Phys. Chem. C* **127**:8148–8158. DOI:10.1021/acs.jpcc.3c01248
137. Zhou J., Chen A., Zhang Y., et al. (2023). 2D ferroionics: Conductive switching mechanisms and transition boundaries in van der Waals layered material CuInP₂S₆. *Adv. Mater.* **35**:2302419. DOI:10.1002/adma.202302419
138. Yang Y., Wang M., He Q., et al. (2025). Ion transport behavior in van der Waals gaps of 2D materials. *Small* **21**:2310681. DOI:10.1002/smll.202310681
139. Li Y., Xiong Y., Zhang X., et al. (2024). Memristors with analogue switching and high on/off ratios using a van der Waals metallic cathode. *Nat. Electron.* **8**:36–45. DOI:10.1038/s41928-024-01269-y
140. Kretschmer S., Ghaderzadeh S., Facsko S., et al. (2022). Threshold ion energies for creating defects in 2D materials from first-principles calculations: Chemical interactions are important. *J. Phys. Chem. Lett.* **13**:514–519. DOI:10.1021/acs.jpclett.1c03995
141. Lee J., Du C., Sun K., et al. (2016). Tuning ionic transport in memristive devices by graphene with engineered nanopores. *ACS Nano* **10**:3571–3579. DOI:10.1021/acsnano.5b07943
142. Kitsios S., Bousoulas P., Spithouris D., et al. (2022). Demonstration of enhanced switching variability and conductance quantization properties in a SiO₂ conducting bridge resistive memory with embedded two-dimensional MoS₂ material. *ACS Appl. Electron. Mater.* **4**:2869–2878. DOI:10.1021/acsaem.2c00362
143. Kang Y., Zhai X., Yang Q., et al. (2025). Conductive dendrite engineering of single-crystalline two-dimensional dielectric memristors. *The Innovation* **6**:100885. DOI:10.1016/j.xinn.2025.100885
144. Nessralla J., Larson D. T., Taniguchi T., et al. (2023). Modulating the electrochemical intercalation of graphene interfaces with α-RuCl₃ as a solid-state electron acceptor. *Nano Lett.* **23**:10334–10341. DOI:10.1021/acs.nanolett.3c02877
145. Liu Q., Lin Y.-C., Kretschmer S., et al. (2023). Molybdenum chloride nanostructures with giant lattice distortions intercalated into bilayer graphene. *ACS Nano* **17**:23659–23670. DOI:10.1021/acsnano.3c06958
146. Hao Z., Chen J., Zhao Q., et al. (2025). Phase transformation induced basal plane capacitance enhancement in two-dimensional materials for electro-driven ion capture. *Nano Lett.* **25**:6753–6761. DOI:10.1021/acs.nanolett.5c00982
147. Kappera R., Voiry D., Yalcin S. E., et al. (2014). Phase-engineered low-resistance contacts for ultrathin MoS₂ transistors. *Nat. Mater.* **13**:1128–1134. DOI:10.1038/nmat4080
148. Cho S., Kim S., Kim J. H., et al. (2015). Phase patterning for ohmic homojunction contact in MoTe₂. *Science* **349**:625–628. DOI:10.1126/science.aab3175
149. Yang H., Huang H., Liu X., et al. (2023). Sensing mechanism of an Au-TiO₂-Ag nanoring based on Fano resonance effects. *Appl. Opt.* **62**:4431–4438. DOI:10.1364/AO.491732
150. Guan J., Shao L., Yu L., et al. (2022). Two-dimensional Mg_{0.2}V₂O₅·nH₂O nanobelts derived from V₄C₃ MXenes for highly stable aqueous zinc ion batteries. *Chem. Eng. J.* **443**:136502. DOI:10.1016/j.cej.2022.136502
151. Rajapakse M., Karki B., Abu U. O., et al. (2021). Intercalation as a versatile tool for fabrication, property tuning, and phase transitions in 2D materials. *npj 2D Mater. Appl.* **5**:30. DOI:10.1038/s41699-021-00211-6
152. Hossain A. K. M. M., McBride J., Mahmoudi Gahrouei M., et al. (2025). Intercalation-induced topotactic phase transformation of tungsten disulfide crystals. *Chem. Mater.* **37**:129–138. DOI:10.1021/acs.chemmater.4c02160
153. Li Y., Yan H., Xu B., et al. (2021). Electrochemical intercalation in atomically thin van der Waals materials for structural phase transition and device applications. *Adv. Mater.* **33**:2000581. DOI:10.1002/adma.202000581
154. Lv R., Robinson J. A., Schaak R. E., et al. (2015). Transition metal dichalcogenides and beyond: synthesis, properties, and applications of single- and few-layer nanosheets. *Acc. Chem. Res.* **48**:56–64. DOI:10.1021/ar5002846
155. Wang P., Yang Y., Pan E., et al. (2022). Emerging phases of layered metal chalcogenides. *Small* **18**:2105215. DOI:10.1002/smll.202105215
156. Tan C., Luo Z., Chaturvedi A., et al. (2018). Preparation of high-percentage 1T-phase transition metal dichalcogenide nanodots for electrochemical hydrogen evolution. *Adv. Mater.* **30**:1705509. DOI:10.1002/adma.201705509
157. Py M. A. and Haering R. R. (1983). Structural destabilization induced by lithium intercalation in MoS₂ and related compounds. *Can. J. Phys.* **61**:76–84. DOI:10.1139/p83-013
158. Xia J., Wang J., Chao D., et al. (2017). Phase evolution of lithium intercalation dynamics in 2H-MoS₂. *Nanoscale* **9**:7533–7540. DOI:10.1039/C7NR02028G
159. Tan S. J. R., Abdelwahab I., Ding Z., et al. (2017). Chemical stabilization of 1T' phase transition metal dichalcogenides with giant optical Kerr nonlinearity. *J. Am. Chem. Soc.* **139**:2504–2511. DOI:10.1021/jacs.6b13238
160. Tan C., Zhao W., Chaturvedi A., et al. (2016). Preparation of single-layer MoS₂Se_{2(1-x)} and Mo_xW_{1-x}S₂ nanosheets with high-concentration metallic 1T phase. *Small* **12**:1866–1874. DOI:10.1002/smll.201600014
161. Arole K., Pas S. E., Thakur R. M., et al. (2024). Effects of intercalation on ML-Ti₃C₂T_z MXene properties and friction performance. *ACS Appl. Mater. Interfaces*

- 16:64156–64165. DOI:10.1021/acsami.4c12659
162. Liu M., Qu X., Wang Y., et al. (2023). Inspired by philosophizing of "point to area": Ion pre-intercalation induces the reconstitution of interlayer environment of MXene for lithium storage. *Chem. Eng. J.* **451**:139015. DOI:10.1016/j.cej.2022.139015
 163. Gao Y., Nan H., Qi R., et al. (2025). Phase-changeable two-dimensional materials: Classification, mechanisms, and applications. *J. Ind. Eng. Chem.* **144**:158–174. DOI:10.1016/j.jiec.2024.10.003
 164. Zhu X., Li D., Liang X., et al. (2019). Ionic modulation and ionic coupling effects in MoS₂ devices for neuromorphic computing. *Nat. Mater.* **18**:141–148. DOI:10.1038/s41563-018-0248-5
 165. Zhai W., Qi J., Xu C., et al. (2023). Reversible semimetal–semiconductor transition of unconventional-phase WS₂ nanosheets. *J. Am. Chem. Soc.* **145**:13444–13451. DOI:10.1021/jacs.3c03776
 166. Yang J., Li X., Gu J., et al. (2025). Reconfigurable ion-migration driven memristor for multistate neuromorphic associative learning. *ACS Photonics* **12**:2574–2582. DOI:10.1021/acsphotonics.5c00023
 167. Mu L., Jiang J., Gao S., et al. (2024). A DFT study of band-gap tuning in 2D black phosphorus via Li⁺, Na⁺, Mg²⁺, and Ca²⁺ ions. *Int. J. Mol. Sci.* **25**:11841. DOI:10.3390/ijms252111841
 168. Zhong Z., Cheng X., Song W., et al. (2025). Reconfigurable logic circuits and rectifier based on two-terminal ionic homojunctions. *Device* **3**:100712. DOI:10.1016/j.device.2025.100712
 169. Belete M., Kataria S., Turfanda A., et al. (2020). Nonvolatile resistive switching in nanocrystalline molybdenum disulfide with ion-based plasticity. *Adv. Electron. Mater.* **6**:1900892. DOI:10.1002/aem.201900892
 170. Tang X., Guo G., Peng Y., et al. (2024). Tunable properties of two-dimensional bilayer C₃N as anode material: Bandgap, binding energy, and diffusion barrier. *J. Energy Storage* **77**:109906. DOI:10.1016/j.est.2023.109906
 171. Butt M. K., Rehman J., Yang Z., et al. (2022). Storage of Na in 2D SnS for Na ion batteries: A DFT prediction. *Phys. Chem. Chem. Phys.* **24**:29609–29615. DOI:10.1039/D2CP002780A
 172. Faini F., Asensio Y., Visentin F., et al. (2025). Imaging ultrafast charge transfer at low-dimensional lead halide perovskite heterostructures. *ACS Energy Lett.* **10**:120–127. DOI:10.1021/acsenenergylett.4c02786
 173. Han B., Sun X., Fan Z., et al. (2024). Enhanced mono/divalent ion separation via charged interlayer channels in montmorillonite-based membranes. *Environ. Sci. Technol.* **58**:4415–4427. DOI:10.1021/acs.est.3c08853
 174. Cheng S., Cao Z., Liu Y., et al. (2024). Ballistic electrolyte ion transport with undisturbed pathways for ultrahigh-rate electrochemical energy storage devices. *Energy Environ. Sci.* **17**:1997–2006. DOI:10.1039/D3EE03819J
 175. Tabandeh Z., Zergani F. and Ghasemi S. (2024). Unveiling silborophene's potential as an anode material for advancing Li ion batteries: DFT and ab-initio molecular dynamics. *J. Energy Storage* **76**:109640. DOI:10.1016/j.est.2023.109640
 176. Ranjan H., Singh C. P., Singh V. P., et al. (2024). Self-rectifying and forming-free resistive switching with Cu/BN/SiO₂/Pt bilayer device. *Mater. Sci. Semicond. Process.* **183**:108744. DOI:10.1016/j.mssp.2024.108744
 177. Pang B., Miao J., Wang H., et al. (2024). Construction of fast charge-transferred OD/2D BiOBr/Bi₂WO₆ S-scheme heterojunction with enhanced photocatalytic performance. *Appl. Surf. Sci.* **649**:159104. DOI:10.1016/j.apsusc.2023.159104
 178. Jia T., Chen Y., Cai Y., et al. (2022). Ferroelectricity and piezoelectricity in 2D van der Waals CuInP₂S₆ ferroelectric tunnel junctions. *Nanomaterials* **12**:2516. DOI:10.3390/nano12152516
 179. Behera R. K., Mishra L., Panigrahi A., et al. (2022). Tunable conductance of MoS₂ and WS₂ quantum dots by electron transfer with redox-active quinone. *ACS Appl. Mater. Interfaces* **14**:5750–5761. DOI:10.1021/acsami.1c18092
 180. Kang M., Lee D. H., Kim J., et al. (2024). Boosting the performance of photomultiplication-type organic photodiodes by embedding CsPbBr₃ perovskite nanocrystals. *Adv. Sci.* **11**:2305349. DOI:10.1002/advs.202305349
 181. Huang C.-H., Cheng T.-Y., Wu C.-Y., et al. (2024). Embedded hybrid-dimensional heterointerface for filament modulation in 2D material-based artificial nociceptor. *Adv. Sci.* **11**:2401946. DOI:10.1002/advs.202401946
 182. Ganeriwala M. D., Luque-Jarava D., Pasadas F., et al. (2025). Effect of grain boundaries on metal atom migration and electronic transport in 2D TMD-based resistive switches. *Nanoscale* **17**:13797–13807. DOI:10.1039/D4NR05321D
 183. Xue F., Zhang C., Ma Y., et al. (2022). Integrated memory devices based on 2D materials. *Adv. Mater.* **34**:2201880. DOI:10.1002/adma.202201880
 184. Wani S.-S., Kuo Y.-R., Kimbulapitiya K. M. M. D. K., et al. (2025). Improved metal–semiconductor interface in monolayer (1L)-MoS₂ via thermally-driven Ag filaments as atomic scale edge contacts triggered by selective annealing process using long wavelength (1064 nm) pulsed laser. *ACS Appl. Mater. Interfaces* **17**:23209–23221. DOI:10.1021/acsami.4c02612
 185. Sun L., Zhang Y., Han G., et al. (2019). Self-selective van der Waals heterostructures for large scale memory array. *Nat. Commun.* **10**:3161. DOI:10.1038/s41467-019-11187-9
 186. Wang Z., Wu H., Burr G. W., et al. (2020). Resistive switching materials for information processing. *Nat. Rev. Mater.* **5**:173–195. DOI:10.1038/s41578-019-0159-3
 187. Sivan M., Li Y., Veluri H., et al. (2019). All WSe₂ 1T1R resistive RAM cell for future monolithic 3D embedded memory integration. *Nat. Commun.* **10**:5201. DOI:10.1038/s41467-019-13176-4
 188. Son D., Chae S. I., Kim M., et al. (2016). Colloidal synthesis of uniform-sized molybdenum disulfide nanosheets for wafer-scale flexible nonvolatile memory. *Adv. Mater.* **28**:9326–9332. DOI:10.1002/adma.201602391
 189. Yin L., Cheng R., Wang Z., et al. (2020). Two-dimensional unipolar memristors with logic and memory functions. *Nano Lett.* **20**:4144–4152. DOI:10.1021/acs.nanolett.0c00002
 190. Park J., Kumar A., Zhou Y., et al. (2024). Multi-level, forming and filament free, bulk switching trilayer RRAM for neuromorphic computing at the edge. *Nat. Commun.* **15**:3492. DOI:10.1038/s41467-024-46682-1
 191. Kaniselman M., Jeon Y. R., Mladenović M., et al. (2025). Mechanisms of resistive switching in two-dimensional monolayer and multilayer materials. *Nat. Mater.* **24**:1346–1358. DOI:10.1038/s41563-025-02170-5
 192. Zhang Z., Zhu X., Wang L., et al. (2025). Quantized conductance in MoS₂ memristors for high-accuracy neuromorphic computing. *J. Phys. D: Appl. Phys.* **58**:215103. DOI:10.1088/1361-6463/adcfac
 193. Kim M.-S. and Kim S. (2024). From oxides to 2D materials: Advancing memristor technologies for energy-efficient neuromorphic computing. *ACS Appl. Electron. Mater.* **6**:3998–4015. DOI:10.1021/acsaelm.4c00428
 194. Pam M. E., Li S., Su T., et al. (2022). Interface-modulated resistive switching in Mo-irradiated ReS₂ for neuromorphic computing. *Adv. Mater.* **34**:2202722. DOI:10.1002/adma.202202722
 195. Choi S., Tan S. H., Li Z., et al. (2018). SiGe epitaxial memory for neuromorphic computing with reproducible high performance based on engineered dislocations. *Nat. Mater.* **17**:335–340. DOI:10.1038/s41563-017-0001-5
 196. Cho Y., Schleder G. R., Larson D. T., et al. (2022). Modulation doping of single-layer semiconductors for improved contact at metal interfaces. *Nano Lett.* **22**:9700–9706. DOI:10.1021/acs.nanolett.2c04011
 197. Huang X., Tong L., Xu L., et al. (2025). 2D MoS₂-based reconfigurable analog hardware. *Nat. Commun.* **16**:101. DOI:10.1038/s41467-024-55395-4
 198. Deng W., Yan X., Wang L., et al. (2024). Two-dimensional materials based memtransistors: integration strategies, switching mechanisms and advanced characterizations. *Nano Energy* **128**:109861. DOI:10.1016/j.nanoen.2024.109861
 199. Ahmed T., Kuriakose S., Tawfik S. A., et al. (2022). Mixed ionic-electronic charge transport in layered black-phosphorus for low-power memory. *Adv. Funct. Mater.* **32**:2107068. DOI:10.1002/adfm.202107068
 200. Sun L., Hwang G., Choi W., et al. (2020). Ultralow switching voltage slope based on two-dimensional materials for integrated memory and neuromorphic applications. *Nano Energy* **69**:104472. DOI:10.1016/j.nanoen.2020.104472
 201. Hua Q., Gao G., Jiang C., et al. (2020). Atomic threshold-switching enabled MoS₂ transistors towards ultralow-power electronics. *Nat. Commun.* **11**:6207. DOI:10.1038/s41467-020-20051-0
 202. Wang X.-F., Tian H., Liu Y., et al. (2019). Two-mode MoS₂ filament transistor with extremely low subthreshold swing and record high on/off ratio. *ACS Nano* **13**:2205–2212. DOI:10.1021/acsnano.8b08876
 203. Mandavkar R., Kulkarni R., Lin S., et al. (2022). Significantly improved photo carrier injection by the MoS₂/ZnO/HNP hybrid UV photodetector architecture. *Appl. Surf. Sci.* **574**:151739. DOI:10.1016/j.apsusc.2021.151739
 204. Li J., Sun J., Lu H., et al. (2024). The study on influence factors of contact properties of metal-MoS₂ interfaces. *Solid-State Electron.* **220**:108992. DOI:10.1016/j.sse.2024.108992
 205. Liu X., Zhang C., Li E., et al. (2024). Ultralow off - state current and multilevel resistance state in van der Waals heterostructure memristors. *Adv. Funct. Mater.* **34**:2309642. DOI:10.1002/adfm.202309642
 206. Feng X., Li Y., Wang L., et al. (2019). A fully printed flexible MoS₂ memristive artificial synapse with femtojoule switching energy. *Adv. Electron. Mater.* **5**:1900740. DOI:10.1002/aem.201900740
 207. Bhattacharjee S., Caruso E., McEvoy N., et al. (2020). Insights into multilevel resistive switching in monolayer MoS₂. *ACS Appl. Mater. Interfaces* **12**:6022–6029. DOI:10.1021/acsami.9b15677
 208. Yang J., Yoon A., Lee D., et al. (2024). Wafer-scale memristor array based on aligned grain boundaries of 2D molybdenum ditelluride for application to artificial synapses. *Adv. Funct. Mater.* **34**:2309455. DOI:10.1002/adfm.202309455
 209. Shen Y.-C., Chen C.-Y., Lee L., et al. (2023). Two-dimensional (2D) materials-inserted conductive bridge random access memory: Controllable injection of cations in vertical stacking alignment of MoSe₂ layers prepared by plasma-assisted chemical vapor reaction. *ACS Mater. Lett.* **5**:1401–1410. DOI:10.1021/acsmaterlett.3c00013
 210. Valov I., Sapezanskaia I., Nayak A., et al. (2012). Atomically controlled electrochemical nucleation at superionic solid electrolyte surfaces. *Nat. Mater.* **11**:530–535. DOI:10.1038/nmat3307
 211. Liu Q., Sun J., Lv H., et al. (2012). Real-time observation on dynamic growth/dissolution of conductive filaments in oxide-electrolyte-based ReRAM. *Adv. Mater.* **24**:1844–1849. DOI:10.1002/adma.201104104
 212. Nikam R. D. and Hwang H. (2022). Atomic threshold switch based on all - 2D material heterostructures with excellent control over filament growth and volatility. *Adv. Funct. Mater.* **32**:2201749. DOI:10.1002/adfm.202201749

213. Wang Z., Joshi S., Savel'ev S. E., et al. (2017). Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing. *Nat. Mater.* **16**:101–108. DOI:10.1038/nmat4756
214. Wang W., Wang M., Ambrosi E., et al. (2019). Surface diffusion-limited lifetime of silver and copper nanofilaments in resistive switching devices. *Nat. Commun.* **10**:81. DOI:10.1038/s41467-018-07979-0
215. Simo A., Polte J., Pfänder N., et al. (2012). Formation mechanism of silver nanoparticles stabilized in glassy matrices. *J. Am. Chem. Soc.* **134**:18824–18833. DOI:10.1021/ja309034n
216. Simonsen S. B., Chorkendorff I., Dahl S., et al. (2011). Ostwald ripening in a Pt/SiO₂ model catalyst studied by in situ TEM. *J. Catal.* **281**:147–155. DOI:10.1016/j.jcat.2011.04.011
217. Xie W., Zhong Y., Wang D., et al. (2023). Co-existence of digital and analog resistive switching in 2D layered BiOI nanosheets for synaptic applications. *Mater. Des.* **234**:112367. DOI:10.1016/j.matdes.2023.112367
218. Pazos S., Xu X., Guo T., et al. (2024). Solution-processed memristors: performance and reliability. *Nat. Rev. Mater.* **9**:358–373. DOI:10.1038/s41578-024-00661-6
219. Zhao Y., Jin Y., Wang X., et al. (2023). A high linearity and energy-efficient artificial synaptic device based on scalable synthesized MoS₂. *J. Mater. Chem. C* **11**:5616–5624. DOI:10.1039/D3TC00438D
220. Nam K., Kim G. Y., Rhee D., et al. (2025). Solution-based manufacturing of 2D materials for memristive device applications. *Int. J. Extreme Manuf.* **7**:052001. DOI:10.1088/2631-7990/add634
221. Aldana S., Jadwiszczak J. and Zhang H. (2023). On the switching mechanism and optimisation of ion irradiation enabled 2D MoS₂ memristors. *Nanoscale* **15**:6408–6416. DOI:10.1039/D2NR06810A
222. Cheng S., Zhong L., Yin J., et al. (2023). Controllable digital and analog resistive switching behavior of 2D layered WSe₂ nanosheets for neuromorphic computing. *Nanoscale* **15**:4801–4808. DOI:10.1039/D2NR06580K
223. Dushaq G., Serunjogi S., Tamalampudi S. R., et al. (2024). Electro-optic tuning in composite silicon photonics based on ferroionic 2D materials. *Light Sci. Appl.* **13**:92. DOI:10.1038/s41377-024-01432-2
224. Deng M., Gao Z., Wang L., et al. (2024). Two-dimensional materials based volatile memristors mediated by flexoelectric effect. *Nano Today* **57**:102332. DOI:10.1016/j.nantod.2024.102332
225. Chen K., Hu H., Song I., et al. (2023). Organic optoelectronic synapse based on photon-modulated electrochemical doping. *Nat. Photonics* **17**:629–637. DOI:10.1038/s41566-023-01232-x
226. Nikam R. D., Kwak M., Lee J., et al. (2020). Controlled ionic tunneling in lithium nanoionic synaptic transistor through atomically thin graphene layer for neuromorphic computing. *Adv. Electron. Mater.* **6**:1901100. DOI:10.1002/aelm.201901100
227. Lee K., Hwang S., Kim D., et al. (2024). 3D stackable vertical-sensing electrochemical random-access memory using ion-permeable WS₂ electrode for high-density neuromorphic systems. *Adv. Funct. Mater.* **34**:2313802. DOI:10.1002/adfm.202313802
228. Li Y., Zhang Z. C., Li J., et al. (2022). Low-voltage ultrafast nonvolatile memory via direct charge injection through a threshold resistive-switching layer. *Nat. Commun.* **13**:4591. DOI:10.1038/s41467-022-32380-3
229. Ji X., Paulsen B. D., Chik G. K. K., et al. (2021). Mimicking associative learning using an ion-trapping non-volatile synaptic organic electrochemical transistor. *Nat. Commun.* **12**:2480. DOI:10.1038/s41467-021-22680-5
230. Kang J.-H., Shin H., Kim K. S., et al. (2023). Monolithic 3D integration of 2D materials-based electronics towards ultimate edge computing solutions. *Nat. Mater.* **22**:1470–1477. DOI:10.1038/s41563-023-01704-z
231. Sangwan V. K., Lee H.-S., Bergeron H., et al. (2018). Multi-terminal memtransistors from polycrystalline monolayer molybdenum disulfide. *Nature* **554**:500–504. DOI:10.1038/nature25747
232. Xu K. and Fullerton-Shirey S. K. (2025). Ionically gated transistors based on two-dimensional materials for neuromorphic computing. *2D Mater.* **12**:023003. DOI:10.1088/2053-1583/adb8c3
233. Kim I.-J., Choi J. and Lee J.-S. (2024). Exploring disturb characteristics in 2D and 3D ferroelectric NAND memory arrays for next-generation memory technology. *ACS Appl. Mater. Interfaces* **16**:33763–33770. DOI:10.1021/acsami.4c03785
234. Das S., Sebastian A., Pop E., et al. (2021). Transistors based on two-dimensional materials for future integrated circuits. *Nat. Electron.* **4**:786–799. DOI:10.1038/s41928-021-00670-1
235. Chung Y. Y., Cheng C. C., Chou Y. C., et al. (2020). High-accuracy deep neural networks using a contralateral-gated analog synapse composed of ultrathin MoS₂ nFET and nonvolatile charge-trap memory. *IEEE Electron Device Lett.* **41**:1649–1652. DOI:10.1109/LED.2020.3026931
236. Farronato M., Melegari M., Ricci S., et al. (2022). Memtransistor devices based on MoS₂ multilayers with volatile switching due to Ag cation migration. *Adv. Electron. Mater.* **8**:2101161. DOI:10.1002/aelm.202101161
237. Wang L., Liao W., Wong S. L., et al. (2019). Artificial synapses based on multiterminal memtransistors for neuromorphic application. *Adv. Funct. Mater.* **29**:1901106. DOI:10.1002/adfm.201901106
238. Hu J., Li H., Zhang Y., et al. (2024). Reconfigurable neuromorphic computing with 2D material heterostructures for versatile neural information processing. *Nano Lett.* **24**:9391–9398. DOI:10.1021/acs.nanolett.4c02658
239. Zhang C., Pudasaini P. R., Oyedele A. D., et al. (2018). Ion migration studies in exfoliated 2D molybdenum oxide via ionic liquid gating for neuromorphic device applications. *ACS Appl. Mater. Interfaces* **10**:22623–22631. DOI:10.1021/acsami.8b05577
240. Melianas A., Kang M.-A., VahidMohammadi A., et al. (2022). High-speed ionic synaptic memory based on 2D titanium carbide MXene. *Adv. Funct. Mater.* **32**:2109970. DOI:10.1002/adfm.202109970
241. Zhang Y., Sun Y., Ren B., et al. (2024). Photoresponse enhancement mechanism of CuInP₂S₆-based device by coupling piezo-phototronic effect and ferroelectric polarization and its application of architecture monitoring. *Nano Energy* **129**:110068. DOI:10.1016/j.nanoen.2024.110068
242. Pan X., Li Y., Cheng B., et al. (2023). 2D materials for intelligent devices. *Sci. China Phys. Mech. Astron.* **66**:117504. DOI:10.1007/s11433-022-2056-1
243. Leng K., Wan Y., Wang X., et al. (2025). Ion intercalation-enabled reconfigurable photodetector with low programming voltage and broadband response based on van der Waals tin disulfide. *Small* **21**:2408545. DOI:10.1002/smll.202408545
244. Pan J., Zhang Y., Yin J., et al. (2025). Principles and applications of two-dimensional semiconductor material devices for reconfigurable electronics. *Nanomaterials* **15**:201. DOI:10.3390/nano15030201
245. Xu M., Chen X., Guo Y., et al. (2023). Reconfigurable neuromorphic computing: Materials, devices, and Integration. *Adv. Mater.* **35**:2301063. DOI:10.1002/adma.202301063
246. Wang T., Meng J., Zhou X., et al. (2022). Reconfigurable neuromorphic memristor network for ultralow-power smart textile electronics. *Nat. Commun.* **13**:7432. DOI:10.1038/s41467-022-35160-1
247. Wang Y., Wu F., Liu X., et al. (2019). High on/off ratio black phosphorus based memristor with ultra-thin phosphorus oxide layer. *Appl. Phys. Lett.* **115**:193503. DOI:10.1063/1.5115531
248. Ge R., Wu X., Kim M., et al. (2018). Atomistor: nonvolatile resistance switching in atomic sheets of transition metal dichalcogenides. *Nano Lett.* **18**:434–441. DOI:10.1021/acs.nanolett.7b04342
249. Li X. D., Cheng W. B., Liu L. L., et al. (2025). Tuning of the resistive switching mechanism in atomistor based on single-defect. *Appl. Phys. Lett.* **126**:103503. DOI:10.1063/5.0256120
250. Lee Y., Huang Y., Chang Y.-F., et al. (2024). Programmable retention characteristics in MoS₂-based atomistors for neuromorphic and reservoir computing systems. *ACS Nano* **18**:14327–14338. DOI:10.1021/acsnano.4c00333
251. Li X.-D., Chen N.-K., Wang B.-Q., et al. (2024). Atomistic memory devices at the thinnest limit: Progress and challenges. *Adv. Mater.* **36**:2307951. DOI:10.1002/adma.202307951
252. Hus S. M., Ge R., Chen P.-A., et al. (2021). Observation of single-defect memristor in an MoS₂ atomic sheet. *Nat. Nanotechnol.* **16**:58–62. DOI:10.1038/s41565-020-00789-w
253. Wu X., Ge R., Chen P.-A., et al. (2019). Thinnest nonvolatile memory based on monolayer h-BN. *Adv. Mater.* **31**:1806790. DOI:10.1002/adma.201806790
254. Dastgeer G., Nisar S., Rasheed A., et al. (2024). Atomistically engineered, high-speed non-volatile flash memory device exhibiting multibit data storage operations. *Nano Energy* **119**:109106. DOI:10.1016/j.nanoen.2023.109106
255. Mallik S. K., Padhan R., Sahu M. C., et al. (2023). Ionotronic WS₂ memtransistors for 6-bit storage and neuromorphic adaptation at high temperature. *npj 2D Mater. Appl.* **7**:63. DOI:10.1038/s41699-023-00427-8
256. 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 Lett.* **16**:121. DOI:10.1007/s40820-024-01335-2
257. Nikam R. D., Lee J., Choi W., et al. (2021). Ionic sieving through one-atom-thick 2D material enables analog nonvolatile memory for neuromorphic computing. *Small* **17**:2103543. DOI:10.1002/smll.202103543
258. Xie M., Jia Y., Nie C., et al. (2023). Monolithic 3D integration of 2D transistors and vertical RRAMs in 1T–4R structure for high-density memory. *Nat. Commun.* **14**:5952. DOI:10.1038/s41467-023-41736-2
259. Sen D., Ravichandran H., Das M., et al. (2024). Multifunctional 2D FETs exploiting incipient ferroelectricity in freestanding SrTiO₃ nanomembranes at sub-ambient temperatures. *Nat. Commun.* **15**:10739. DOI:10.1038/s41467-024-54231-z
260. Tang B., Veluri H., Li Y., et al. (2022). Wafer-scale solution-processed 2D material analog resistive memory array for memory-based computing. *Nat. Commun.* **13**:3037. DOI:10.1038/s41467-022-30519-w
261. Sebastian A., Le Gallo M., Khaddam-Aljameh R., et al. (2020). Memory devices and applications for in-memory computing. *Nat. Nanotechnol.* **15**:529–544. DOI:10.1038/s41565-020-0655-z
262. Ielmini D. and Wong H. S. P. (2018). In-memory computing with resistive switching devices. *Nat. Electron.* **1**:333–343. DOI:10.1038/s41928-018-0092-2
263. Verma N., Jia H., Valavi H., et al. (2019). In-memory computing: Advances and prospects. *IEEE Solid-State Circuits Mag.* **11**:43–55. DOI:10.1109/MSSC.2019.2922889
264. Liu X.-T., Chen J.-R., Wang Y., et al. (2021). Building functional memories and logic circuits with 2D boron nitride. *Adv. Funct. Mater.* **31**:2004733. DOI:10.1002/adfm.

- 202004733
265. Wang Y., Sun Q., Yu J., et al. (2023). Boolean logic computing based on neuromorphic transistor. *Adv. Funct. Mater.* **33**:2305791. DOI:10.1002/adfm.202305791
 266. Krishnaprasad A., Dev D., Han S. S., et al. (2022). MoS₂ synapses with ultra-low variability and their implementation in Boolean logic. *ACS Nano* **16**:2866–2876. DOI:10.1021/acsnano.1c09904
 267. Li Y., Xiong Y., Zhai B., et al. Ag-doped non-imperfection-enabled uniform memristive neuromorphic device based on van der Waals indium phosphorus sulfide. *Sci. Adv.* **10**:eadk9474. DOI:10.1126/sciadv.adk9474
 268. Liu L., Li Y., Huang X., et al. (2021). Low - power memristive logic device enabled by controllable oxidation of 2D HfSe₂ for in - memory computing. *Adv. Sci.* **8**:2005038. DOI:10.1002/advs.202005038
 269. Liu J., Feng G., Li W., et al. (2025). Physical reservoir computing for Edge AI applications. *Innov. Mater.* **3**:100127. DOI:10.59717/j.xinn-mater.2025.100127
 270. Yin L., Cheng R., Wen Y., et al. (2021). Emerging 2D memory devices for in-memory computing. *Adv. Mater.* **33**:2007081. DOI:10.1002/adma.202007081
 271. Cao G., Meng P., Chen J., et al. (2021). 2D material based synaptic devices for neuromorphic computing. *Adv. Funct. Mater.* **31**:2005443. DOI:10.1002/adfm.202005443
 272. Zhang Z., Yang D., Li H., et al. (2022). 2D materials and van der Waals heterojunctions for neuromorphic computing. *Neuromorph. Comput. Eng.* **2**:032004. DOI:10.1088/2634-4386/ac8a6a
 273. Thakar K., Rajendran B. and Lodha S. (2023). Ultra-low power neuromorphic obstacle detection using a two-dimensional materials-based subthreshold transistor. *npj 2D Mater. Appl.* **7**:68. DOI:10.1038/s41699-023-00422-z
 274. Lee E., Kim J., Bhoyate S., et al. (2020). Realizing scalable two-dimensional MoS₂ synaptic devices for neuromorphic computing. *Chem. Mater.* **32**:10447–10455. DOI:10.1021/acs.chemmater.0c03112
 275. Hu J., Li B., Wang H., et al. (2025). Self - compliant, variation - suppressed memristor implemented with carbon nanotube/hBN/silver nanowire cross - point structure. *Adv. Funct. Mater.* **35**:2424131. DOI:10.1002/adfm.202424131
 276. Verhage M., Maia A. S., Plomp J. J., et al. (2000). Synaptic assembly of the brain in the absence of neurotransmitter secretion. *Science* **287**:864–869. DOI:10.1126/science.287.5454.864
 277. Lee G., Baek J.-H., Ren F., et al. (2021). Artificial neuron and synapse devices based on 2D materials. *Small* **17**:2100640. DOI:10.1002/smll.202100640
 278. Kwak K. J., Baek J. H., Lee D. E., et al. (2022). Ambient stable all inorganic CsCu₂I₃ artificial synapses for neurocomputing. *Nano Lett.* **22**:6010–6017. DOI:10.1021/acs.nanolett.2c01272
 279. Kim S. J., Lee H.-J., Lee C.-H., et al. (2024). 2D materials-based 3D integration for neuromorphic hardware. *npj 2D Mater. Appl.* **8**:70. DOI:10.1038/s41699-024-00509-1
 280. Ren Y., Wang Y., Xiong Z. Y., et al. (2024). Reconfigurable artificial perception system and logic gates based on large - scale antiambipolar 2D heterostructure array. *Adv. Funct. Mater.* **35**:2417358. DOI:10.1002/adfm.202417358
 281. Jo Y., Woo D. Y., Noh G., et al. (2024). Hardware implementation of network connectivity relationships using 2D hBN - based artificial neuron and synaptic devices. *Adv. Funct. Mater.* **34**:2309058. DOI:10.1002/adfm.202309058
 282. Indiveri G. and Liu S. C. (2015). Memory and information processing in neuromorphic systems. *Proc. IEEE* **103**:1379–1397. DOI:10.1109/JPROC.2015.2444094
 283. Fuller E. J., Keene S. T., Melianas A., et al. (2019). Parallel programming of an ionic floating-gate memory array for scalable neuromorphic computing. *Science* **364**:570–574. DOI:10.1126/science.aaw5581
 284. Burr G. W., Sebastian A., Ando T., et al. (2021). Ohm's law + Kirchhoff's current law = better AI: Neural-network processing done in memory with analog circuits will save energy. *IEEE Spectr.* **58**:44–49. DOI:10.1109/MSPEC.2021.9641759
 285. Guo T., Zhang B., Wang X., et al. (2023). Broadband optoelectronic synapse enables compact monolithic neuromorphic machine vision for information processing. *Adv. Funct. Mater.* **33**:2303879. DOI:10.1002/adfm.202303879
 286. Alaba F. A., Othman M., Hashem I. A. T., et al. (2017). Internet of Things security: A survey. *J. Network Comput. Appl.* **88**:10–28. DOI:10.1016/j.jnca.2017.04.002
 287. Jerry M., Ni K., Parihar A., et al. (2018). Stochastic insulator-to-metal phase transition-based true random number generator. *IEEE Electron Device Lett.* **39**:139–142. DOI:10.1109/LED.2017.2771812
 288. Wali A. and Das S. (2023). Hardware and information security primitives based on 2D materials and devices. *Adv. Mater.* **35**:2205365. DOI:10.1002/adma.202205365
 289. Liu B., Chang Y.-F., Li J., et al. (2022). Bi₂O₂Se-based true random number generator for security applications. *ACS Nano* **16**:6847–6857. DOI:10.1021/acsnano.2c01784
 290. Wen C., Li X., Zanotti T., et al. (2021). Advanced data encryption using 2D materials. *Adv. Mater.* **33**:2100185. DOI:10.1002/adma.202100185
 291. Han T., Aguirre F., Zhu K., et al. (2024). Fully 2D materials-based resistive switching circuits for advanced data encryption. *Adv. Funct. Mater.* **34**:2403029. DOI:10.1002/adfm.202403029
 292. Zhu K., Vescio G., González-Torres S., et al. (2023). Inkjet-printed h-BN memristors for hardware security. *Nanoscale* **15**:9985–9992. DOI:10.1039/D3NR00030C
 293. Shi Y., Ni L., Wang Z., et al. (2024). Ultrathin two-dimensional materials: New opportunities and challenges in ultra-sensitive gas sensing. *Coord. Chem. Rev.* **505**:215691. DOI:10.1016/j.ccr.2024.215691
 294. Hassan J. Z., Raza A., Din Babar Z. U., et al. (2023). 2D material-based sensing devices: An update. *J. Mater. Chem. A* **11**:6016–6063. DOI:10.1039/D2TA07653E
 295. Li S. and Zhang L. (2024). Accurate first-principles simulation for the response of 2D chemiresistive gas sensors. *npj Comput. Mater.* **10**:138. DOI:10.1038/s41524-024-01329-z
 296. Youn H.-Y., Choi T.-Y., Shim J., et al. (2025). Soft sputtering of large-area 2D MoS₂ layers using isolated plasma soft deposition for humidity sensors. *Adv. Mater.* **37**:2414800. DOI:10.1002/adma.202414800
 297. Maity A., Pu H., Sui X., et al. (2023). Scalable graphene sensor array for real-time toxins monitoring in flowing water. *Nat. Commun.* **14**:4184. DOI:10.1038/s41467-023-39701-0
 298. Xue M., Mackin C., Weng W.-H., et al. (2022). Integrated biosensor platform based on graphene transistor arrays for real-time high-accuracy ion sensing. *Nat. Commun.* **13**:5064. DOI:10.1038/s41467-022-32749-4
 299. Saravanan A., Huang B.-R., Hwang S.-K., et al. (2024). Photovoltaic induced self-powered gas sensor based on 2D MoS₂ incorporated NbSe₂ nanorods heterostructure for NH₃ gas sensing at room temperature. *Chem. Eng. J.* **491**:151795. DOI:10.1016/j.cej.2024.151795
 300. Zhang W., Qin J., Lai S., et al. (2025). Surface engineering enabled highly sensitive humidity sensors in two-dimensional hexagonal boron nitride nanosheets. *Nano Res.* **18**:94907405. DOI:10.26599/NR.2025.94907405
 301. Masud, Song J., Ahmed F., et al. (2025). 2D materials: From design and synthesis to applications in electrical and electrochemical biosensors. *Small* **21**:e04955. DOI:10.1002/smll.202504955
 302. Chen M., Ma Y., Aslam N., et al. (2025). Ultrawide-bandwidth boron nitride photonic memristors. *Nat. Nanotechnol.* **20**:1633–1640. DOI:10.1038/s41565-025-01991-4
 303. Du J.-y., Ge C., Riahi H., et al. (2020). Dual-gated MoS₂ transistors for synaptic and programmable logic functions. *Adv. Electron. Mater.* **6**:1901408. DOI:10.1002/aeml.201901408
 304. Wang S., Zhou Z., Yang F., et al. (2023). All-atomristor logic gates. *Nano Res.* **16**:1688–1694. DOI:10.1007/s12274-022-5042-7
 305. Lu X. F., Zhang Y., Wang N., et al. (2021). Exploring low power and ultrafast memristor on p-type van der Waals SnS. *Nano Lett.* **21**:8800–8807. DOI:10.1021/acs.nanolett.1c03169
 306. Chen K., Lu G., Chang J., et al. (2012). Hg(II) ion detection using thermally reduced graphene oxide decorated with functionalized gold nanoparticles. *Anal. Chem.* **84**:4057–4062. DOI:10.1021/ac3000336
 307. Dang W., Shen Y., Wei W., et al. Mortise-tenon-shaped memristors for scientific computing. *Sci. Adv.* **11**:eadu3309. DOI:10.1126/sciadv.adu3309
 308. Jayachandran D., Pendurthi R., Sadaf M. U. K., et al. (2024). Three-dimensional integration of two-dimensional field-effect transistors. *Nature* **625**:276–281. DOI:10.1038/s41586-023-06860-5
 309. Ghosh S., Zheng Y., Zhang Z., et al. (2024). Monolithic and heterogeneous three-dimensional integration of two-dimensional materials with high-density vias. *Nat. Electron.* **7**:892–903. DOI:10.1038/s41928-024-01251-8

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The data that support the findings of this study are available upon reasonable request.