Ion-Mediated Oxide Transistors for Neuromorphic Electronics: Materials, Devices, and Perspectives

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ABSTRACT

Constrained by the physical architecture of von Neumann computing with separated storage and computation, neuromorphic computing architectures have been proposed. Ion-mediated oxide synaptic transistors (IOSTs), with their unique bio-mimetic characteristics, have become a key fundamental component in the construction of neuromorphic computing systems. This review comprehensively explores the biomimetic principles and critical indicators of IOSTs, and discusses the unique advantages and recent developments associated by employing various electrolyte materials as the dielectric layers in IOSTs, including ionic liquids, ionic gels, organic polymer electrolytes, and inorganic solid electrolytes. Furthermore, we explore the extensive applications of IOSTs across multiple domains, such as multisensory bionics and neuromorphic computing. This article provides an exhaustive perspective on the research related to IOSTs and their system integration and applications, offering insights into their evolving landscape in neuromorphic electronics.

I. INTRODUCTION

The traditional von Neumann computing architecture separates the computation unit and the storage unit, leading to a mismatch between the data process the data transfer speed, which constrains the processing performance of computers. This limitation becomes particularly evident when confronting the massive computational power required in the information age, resulting in underperformance.[1-3] Consequently, there is an urgent need to develop new computing paradigms to meet the increasing demands for data processing. Among various candidates, neuromorphic computing, which emulates the human brain's method of processing information through a parallel processing architecture, is considered one of the promising new computational architectures capable of achieving higher efficiency and lower energy consumption.[4-6] Developing underlying electronic devices that can simulate neuronal and synaptic behaviors is a valuable research topic for building neuromorphic computing architectures. This is also a crucial approach to addressing current computational challenges and paving the way for new chapters in future computing technologies.

Over the past few decades, conventional complementary metal-oxide-semiconductor (CMOS) technology has advanced considerably. However, implementing synaptic functions with CMOS circuits typically requires dozens of transistors, resulting in large area consumption and high power dissipation, which constrains the large-scale integration of neural networks.[3, 7] Moreover, CMOS technology lacks the dynamic plasticity of biological synapses, making it challenging to achieve real-time weight adjustment and learning functions efficiently. These limitations have driven researchers to explore novel devices for more effective artificial synapse emulation. In recent developments within the field of neuromorphic electronic devices, significant research advancements have been achieved in two-terminal devices such as memristors,[8-12] phase change memories,[13, 14] resistive random access memory,[15-17] and atomic switches.[18] The broad application of these devices is attributed to their simple structures and compact sizes, which facilitate easier manufacturing and integration. They offer advantages in terms of power consumption and switching speed, making them well-suited for neuromorphic computing architectures that require large-scale parallel computations. However, in two-terminal devices, both the reading and writing processes occur through the same current path. As a result, the read and write currents may induce crosstalk during operation, potentially affecting the reliable modulation of the device. The three-terminal devices can effectively separate reading and writing operations, present another attractive solution. These devices can support both learning and memory functions concurrently. Additionally, by utilizing the third terminal, a precise modulation of conductance can be achieved, thereby offering greater controllability, flexibility, and stability.[19]

In three-terminal synaptic transistor devices, the semiconductor layer serves as a channel mediating current conduction. Traditional semiconductor materials include silicon, germanium, and gallium arsenide, while organic materials,[20-24] two-dimensional materials,[25, 26] and oxide materials also emerge as competitive candidates for semiconductor applications. Researchers have constructed many high-performance three-terminal synaptic transistor devices using these materials. Among these materials, oxide semiconductors possess unique advantages.[27] In 2004, Kenji Nomura *et al.* pioneered the use of indium gallium zinc oxide (IGZO) in thin-film transistors, significantly advancing the development of metal oxide semiconductor devices.[28] Beyond IGZO, which has been extensively studied,[29, 30] other popular oxide semiconductor materials, such as ZnO,[31, 32] SnO_2,[33] In_2O_3,[34] Ga_2O_3,[35] IZO,[36, 37] ITO,[38] and IWO,[39] have also sparked a new wave of research. Oxide semiconductors typically feature wide band gaps, which endow them with excellent transparency and effective photoresponse characteristics within suitable wavelength ranges.[40] Furthermore, the abundance and low cost of raw materials for oxide semiconductors offer advantages in cost control for devices based on these materials. In terms of fabrication, oxide semiconductors can be prepared using various well-established techniques, such as sol-gel methods,[41] magnetron sputtering deposition,[42] chemical vapor deposition,[43] and atomic layer deposition (ALD).[44] Compared to two-dimensional materials, these methods provide superior capabilities for integration and large-scale production. Additionally, oxide semiconductors maintain robust electrical performance and chemical stability even in harsh environments.[39] Therefore, compared to traditional semiconductor and organic semiconductor devices, oxide semiconductor devices demonstrate superior stability and reliability. Moreover, oxide semiconductors have broad prospects in flexible electronics, such as bendable displays, flexible solar cells, and wearable sensors,[45] owing to their excellent flexibility, pliability, and photosensitivity.

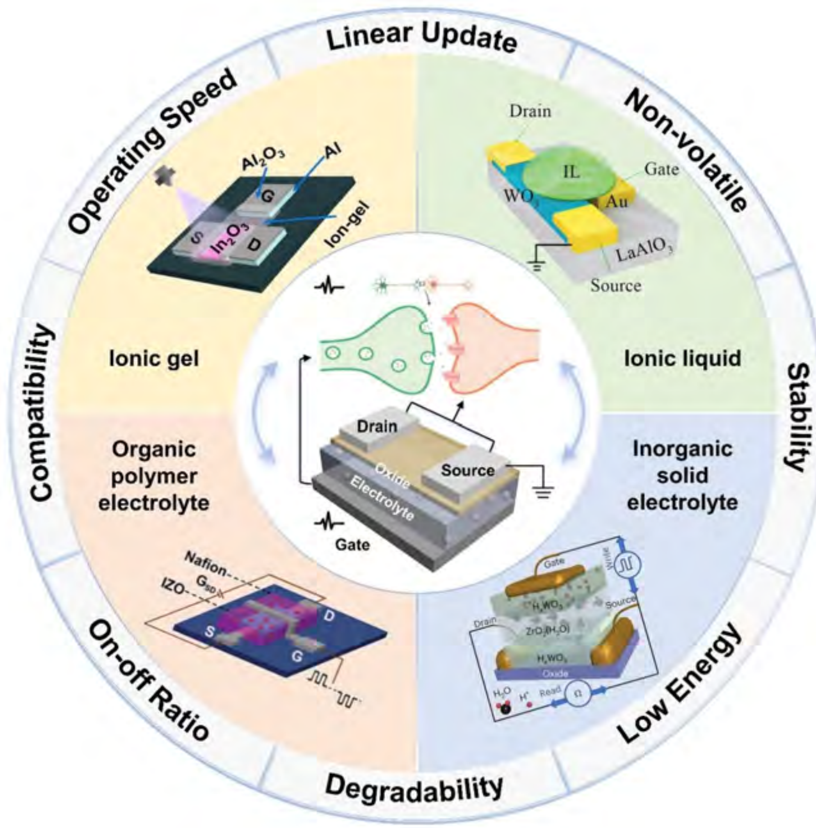

FIG. 1. The four types of IOSTs and their performance metrics that should be considered. Counterclockwise from the top left: In_2O_3 IOST based on ionic gel [Reproduced with permission from Jin *et al.*, Nano Lett. **22**, 3372 (2022).[46] Copyright 2022 American Chemical Society], IZO IOST using Nafion electrolyte [Reproduced with permission from Mohanty *et al.*, ACS Appl. Mater. Interfaces **15**, 19279 (2023).[47] Copyright 2023 American Chemical Society], WO_3 IOST based on inorganic solid-state electrolyte [Reproduced with permission from Cui *et al.*, Nat. Electron. **6**, 292 (2023).[48] Copyright 2023 Springer Nature], and WO_3 IOST utilizing ionic liquids [Reproduced with permission from Yang *et al.*, Adv. Mater. **30**, 1801548 (2018).[49] Copyright 2018 John Wiley & Sons, Inc.]. Parts of the central synapse schematic were created in BioRender.

The dielectric layer, as another critical component of three-terminal synaptic transistors, demonstrates significant advantages when electrolyte materials containing controllable ions are employed.[50] Compared to devices using other dielectric materials, such as ferroelectric materials, synaptic devices based on electrolyte materials containing controllable ions exhibit functionality similar to biological systems, offering superior bio-similarity and biocompatibility. This is advantageous for the development of neuromorphic computing systems and holds potential for applications in brain-machine interfaces. Besides, ion-mediated devices typically operate at ultra-low voltages, without requiring high operating voltages to switch the polarization state of the material, which is significant for low-power computing applications.[51-53] In terms of modulation mechanisms, ion migration within the electrolyte material establishes strong electric fields and large specific capacitance within the device, promoting effective carrier modulation. Furthermore, the diversity in ion size, valence state, and polarizability offers a wide range of strategies for tuning device performance.[54]

This article focuses on research related to ion-mediated oxide synaptic transistors (IOSTs), detailing the emulation of biological synapses by IOST devices, and describing the performance metrics that should be considered during the fabrication and testing of these devices. Furthermore, we discuss various electrolyte materials, including ionic liquids, ionic gels, organic polymer electrolytes, and inorganic solid electrolytes, highlighting their unique advantages and recent developments as dielectric layers in IOSTs, as illustrated in Fig. 1. Additionally, we anticipate the extensive applications of IOSTs, ranging from multisensory bionics to neuromorphic computing. In summary, due to their outstanding performance and wide application prospects, IOSTs are considered indispensable foundational components in emerging neuromorphic computing architectures. Through a comprehensive review of these devices, this article aims to provide a thorough perspective on the recent advancements and applications.

II. BIOMIMETIC PERFORMANCE OF ION-MEDIATED OXIDE SYNAPTIC TRANSISTORS

A. Overview of the Biomimetic Functionality of IOSTs

In the neuromorphic system of the human brain, neuromorphic synapses are responsible for transmitting biological information.[55] The human brain comprises approximately 10^{11} neurons interconnected by 10^{15} synapses.[56] When a neuron is activated by external stimuli, it conducts an electrical signal (action potential) along its axon, leading to the opening of Ca^{2+} channels in the presynaptic membrane. This influx of Ca^{2+} further promotes the fusion of vesicles containing neurotransmitters with the presynaptic membrane, and the release of neurotransmitters into the synaptic cleft. The neurotransmitters then diffuse and bind to receptors on the postsynaptic membrane, causing specific ion channels to open or close, thereby altering the electrical potential of the postsynaptic membrane.[49] This process forms the basis for information transmission in the neural system of the human brain and is a fundamental mechanism of information transfer in the nervous system. IOSTs can effectively simulate this mechanism. They consist of three terminals: gate, source, and drain. The gate is considered the terminal for applying action potentials, simulating the presynaptic membrane, while the channel between the source and drain is made of oxide materials, mimicking the postsynaptic membrane. Between the channel and the bottom gate, there is a layer of electrolyte material containing controllable ions, which enhances the modulation of the channel carriers. The structure of the IOST device is illustrated in the schematic of the central synapse in Fig. 1. When a stimulus is applied to the gate, ions in the electrolyte material migrate, thereby affecting the change in channel conductance. This simulates the transmission of the stimulus signal between two synaptic unit devices.

In addition, synaptic weight is a critical concept in signal transmission, reflecting the efficiency of signal propagation. Synaptic plasticity refers to the adjustability of the connection strength between synapses, which serves as the basis for learning and memory in biological brains, allowing the system to respond and adjust to external stimuli.[57] Synaptic plasticity typically includes long-term plasticity (LTP) and short-term plasticity (STP). LTP is often associated with long-term learning and memory, while STP is used for temporary adjustments in response to immediate events.[58] In IOSTs, when the stimulus is continuously applied to the gate, non-volatile/volatile changes occur in the channel conductance (current) between the source and drain, which simulates biological synapses' LTP/STP. This current is called excitatory post-synaptic current (EPSC), and this plasticity can be modulated externally.[59, 60] Additionally, the connection strength between IOSTs may be potentiated or depressed by external stimuli, classified into long-term potentiation, long-term depression, short-term potentiation, and short-term depression. Furthermore, paired-pulse facilitation (PPF) and spike-timing-dependent plasticity (STDP) also reflect adjustments in synaptic weight,[61] which are crucial for information encoding, processing, and storage in neuromorphic computing systems. Building on the above, IOSTs can construct artificial neural networks (ANNs) through crossbar arrays. Each IOST device serves as a crosspoint in the array, simulating the synaptic weighting effect, and regulating the conductance through gate voltage to enable signal transmission and learning between neurons. This array structure allows the IOSTs to adaptively adjust connection weights in large-scale parallel computing, thereby achieving neural network training and pattern recognition.

B. Device Performance Metrics of IOSTs

To achieve more efficient neuromorphic computing, several performance metrics are typically prioritized in the research, fabrication, and testing of IOSTs. These include: I. Linearity and symmetry in conductance updates. They are crucial for brain-inspired computing, and considerable efforts have been made to enhance these aspects.[62] For instance, Nikam *et al.* improved the ionic conductivity of Li_3PO_4 inorganic solid films through Se doping, reducing the activation energy for lithium ion migration, which improves linearity and symmetry in conductance updates.[63] Additionally, optimizing channel material stoichiometry and interface traps also contributes to these characteristics.[64-67] II. Non-volatility. The duration a device maintains a single conductance level during multilevel conductance state changes is a critical indicator of an IOST's storage capability. Interface instability may lead to device volatility, which can be optimized by inserting barrier layers.[68, 69] III. Operational speed. The rapid operational speed of IOSTs allows them to respond instantaneously to external stimuli for real-time information processing. The subthreshold swing (SS) effectively reflects the speed of conductance change,[70] numerally equivalent to the gate voltage change required to alter the channel current by an order of magnitude. IV. Energy consumption. Each synaptic event in the human brain requires only 1-100 fJ of energy.[71] Research on IOSTs has achieved energy consumptions reduced to the sub-femtojoule level, lower than biological synapses.[72] Additionally, the threshold voltage and the levels of read-write currents also impact the power consumption of the device.[73] V. Stability. Stability ensures the device functions smoothly in the presence of noise, temperature, or other external disturbances. Spatiotemporal stability is often considered, which encompasses the stability of a single device over time and the uniformity of performance among devices from the same batch.[74] In 2023, Qing Cao's team reported hydrogenated tungsten oxide IOSTs capable of reliable read-write operations over 100 million cycles.[48] Other important metrics, such as high on-off ratios,[75] and compatibility with CMOS technology,[76, 77] are also worthy of further research and improvement.

III. ELECTROLYTE MATERIALS FOR ION-MEDIATED OXIDE SYNAPTIC TRANSISTORS

IOSTs exhibit significant advantages due to their high similarity to the working mechanisms of biological synapses, specifically by using ion migration to dynamically modulate channels, thus enabling highly sensitive and adjustable responses to signals.[78] Commonly modulated ions include protons, Li^+, Na^+, and O^{2-}. Protons, with the smallest ionic radius, can move quickly under an electric field and easily embed into the interstitial spaces of channel layers,[79] providing proton-based devices with high sensitivity, high modulation speed, and low power consumption.[80] However, their retention performance is limited to seconds to hours,[81] and some proton reservoir materials are vulnerable to atmospheric humidity,[48] which hinders their application. Research related to solid-state lithium batteries is burgeoning, offering useful insights for Li^+-mediated IOSTs. The small ionic radius and high diffusion coefficient of lithium ions have drawn widespread attention, though compatibility with CMOS and multi-level conductance retention capabilities need consideration.[82-85] Na^+ is considered a low-cost, environmentally friendly ion, with favorable interactions with water. Devices based on sodium ions are simple to fabricate, and sodium ion doping can be directly accomplished by soaking in a sodium chloride solution.[86] Moreover, Na^+ has a lower diffusion rate than Li^+, contributing to the non-volatility of devices.[69] Additionally, O^{2-} based devices have also been extensively studied. Oxygen ions have a high migration energy, limiting the modulation speed of devices. However, on the other hand, high migration energy can reduce spontaneous diffusion, thereby achieving high retention performance in devices. Furthermore, devices mediated by other ions such as K^+,[87] F^-,[88] and Mg^{2+},[89] as well as dual-ion modulation devices have also been reported.[90] Specific ion-mediated devices can be used according to different materials and requirements.

In recent years, IOSTs have been widely studied. In the design of these devices, the electrolyte materials play a critical role in addition to the oxide semiconductor layer. Here, we primarily discuss devices where the electrolyte dielectric layers are composed of ionic liquids, ionic gels, organic polymer electrolytes, and inorganic solid electrolytes. The following section will present an overview and recent developments of IOSTs employing various dielectric layer materials.

A. Ionic-Liquids-Mediated Oxide Synaptic Transistor

Among various electrolyte materials, ionic liquids stand out for their high ionic conductivity and tunability. Ionic liquids consist of free ions with different polar charges that move to the film interface under potentiated gate voltage, forming an electric double layer (EDL), thus enabling electrostatic field mediation [Fig. 2(a)]. When the gate voltage exceeds a certain threshold, ions may penetrate the interface and embed into the semiconductor channel, inducing electrochemical modulation [Fig. 2(b)].[91, 92] This phenomena can be verified through characterization techniques and first-principles calculations.[93] Under electric fields, ions in the ionic liquids facilitate rapid conduction, effectively modulating channel conductance and achieving high switching speeds, which are crucial for applications requiring fast responses, such as high-frequency communication and rapid image processing. Additionally, the preparation of ionic liquids is straightforward. It can be directly applied via pipetting onto the sample to serve as the dielectric layer connecting the channel and gate electrode.[81]

In recent years, research on ionic liquids materials has proliferated. Controlling the reversible phase transition modulation of the channel is an effective means of achieving artificial synaptic behaviors.[94] In 2018, Yang *et al.* developed a [DEME][TFSI]-gated WO_3 IOST. This device exhibits different channel conductance modulation mechanisms when subjected to varying gate voltages [Fig. 2(c)].[49] Specifically, when a positive gate voltage below the hydrolysis reaction threshold (V_T) is applied, an EDL forms at the interface between the ionic liquids and the channel. When the applied gate voltage exceeds V_T, hydrolysis occurs within the ionic liquids, producing H^+ and OH^-, with protons embedding into the WO_3 channel to form H_xWO_3, thereby affecting the channel conductance. Similarly, Yang *et al.* proposed an IOST using an [EMIM][TFSI]-gated quasi-two-dimensional α-MoO_3 nanosheet, where protons reversibly and non-volatily modulate the α-MoO_3 channel conductance [Fig. 2(d)].[95] These studies demonstrate that by precisely controlling the gate voltage, effective modulation of the ion liquid-material interface can be achieved, further enhancing the tunability and flexibility of the device. In addition, perovskite, a class of ceramic oxide materials, is often used in conjunction with ionic liquids in IOSTs. In 2019, Huang *et al.* demonstrated an IOST based on an $SrCoO_x$ (SCO) film. When a gate voltage is applied, the EDL generated within [DEME][TFSI] ionic liquids prompts hydrolysis, leading to the insertion or extraction of oxygen ions into or from the SCO channel. This process results in a phase transition and modifies the conductivity. The device can also simulate changes in synaptic weight by varying pulse amplitude and number, achieving multilevel non-volatile conductance states [Fig. 2(e)].[81] This highlights the potential of perovskite materials in IOST devices and provides new insights for synaptic device development. However, the hydrolysis process may accelerate material degradation over time, leading to long-term stability issues for the device. Additionally, the modulation of oxygen vacancy concentration represents another typical mechanism.[77, 96] In 2023, Alejandro López *et al.* utilized an ionic liquid [DEME][TFSI] to modulate the conductivity of the $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) channel through reversible electrochemical oxygen exchange, enabling both LTP and STP by modulating gate voltage [Fig. 2(f)].[97] Shi *et al.* developed an ionic liquids-gated $SmNiO_3$ transistor, revealing the impact of oxygen vacancies on conductivity modulation, which is associated with defect formation and electron scattering mechanisms.[98]

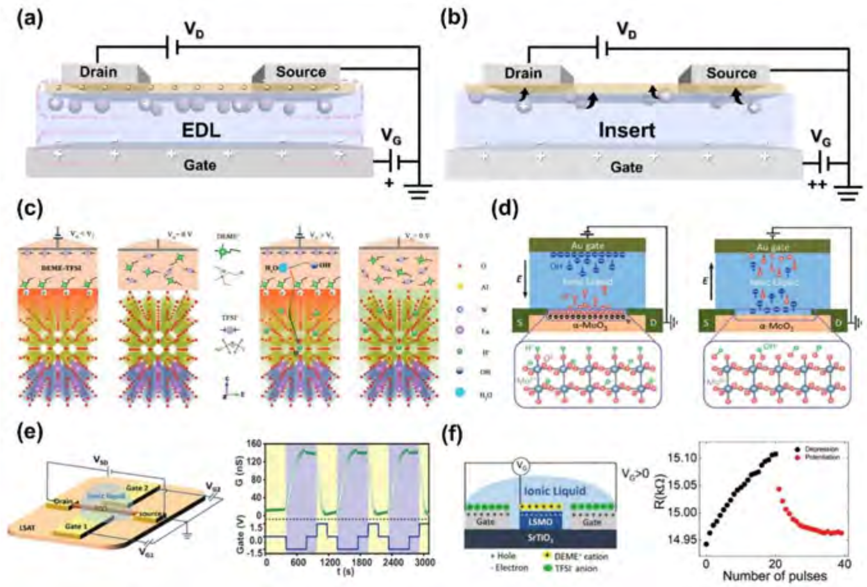

FIG. 2. (a) Formation of the EDL at low gate voltage. (b) Ion embedding into the channel when the applied gate voltage exceeds the threshold. (c) Formation of the EDL and relaxation processes at gate voltages below the threshold required for hydrolysis, and proton embedding in the channel and relaxation processes at gate voltages above the threshold required for hydrolysis. Reproduced with permission from Yang *et al.*, Adv. Mater. **30**, 1801548 (2018).[49] Copyright 2018 John Wiley & Sons, Inc. (d) Proton transfer to the interface and embedding under positive gate voltage, and proton extraction and desorption under negative gate voltage. Reproduced with permission from Yang *et al.*, Adv. Mater. **29**, 1700906 (2017).[95] Copyright 2017 John Wiley & Sons, Inc. (e) A [DEME][TFSI]-gated SCO IOST and conductance modulation and retention characteristics under continuously potentiating or depressing gate voltages. Reproduced with permission from Huang *et al.*, Adv. Funct. Mater. **29**, 1902702 (2019).[81] Copyright 2019 John Wiley & Sons, Inc. (f) Electrostatic modulation schematic of a [DEME][TFSI]-gated LSMO IOST under positive gate voltage and its LTP. Reproduced with permission from López *et al.*, Adv. Electron. Mater. **9**, 2300007 (2023),[97] licensed under a Creative Commons Attribution (CC BY) license.

B. Ionic-Gel-Mediated Oxide Synaptic Transistor

Although oxide transistors based on ionic liquids offer advantages in switching speed and ion conduction, their retention and application in complex circuits, particularly in terms of integration, must also be considered. To address this challenge, the use of ionic gels dielectric layers has been proposed. Ionic gels are formed by combining ionic liquids with polymers or networked materials. Compared to ionic liquids, ionic gels combine the excellent ionic conductivity of ionic liquids with the mechanical stability and ease of processing of gel materials, additionally reducing the risk of leakage.

In terms of mechanical structure, ionic gels are typically soft materials with a certain degree of tensile strength,[99] enabling compatibility with flexible electronic devices and adaptation to device of various shapes and sizes.[100] In 2021, VO_2 Mott transistors gated by rubbery solid ionic gels were stably operated on flexible substrates. The ionic gel consists of [DEME][BF_4] and copolymer of PVDF-HFP. The gate voltage modulation induced the VO_2 metal-insulator transition, facilitating the conversion of STP to LTP [Figs. 3(a) and 3(b)].[101] In the same year, Seyong Oh *et al.* fabricated flexible artificial synapses based on silicon-indium-zinc oxide (SIZO) with ionic gel gating on a polyimide substrate, and integrated stretchable resistive sensors to construct a sensory neuromorphic system for sign language translation [Figs. 3(c) and 3(d)].[102] These works demonstrate the potential of combining ion gels with flexible materials, providing a new pathway for the development of intelligent interactive systems. The ionic contained in the ionic gel can induce charges at the interface between the channel layer and the ionic gel dielectric layer. By adjusting the polymer matrix or the ratio of ionic liquids in the ionic gel, its mechanical properties, such as softness, elasticity, and viscosity, can be optimized.[103] Reducing the device size and enhancing the capacitance-frequency and conductance-frequency responses of the gel materials can improve switching frequency and reduce power consumption.[100, 104] Additionally, the introduction of nanoparticles between the ionic gel and channel layer can further enhance device performance.[105] Crosslinking technology, which introduces chemical bonds or physical links between polymer molecules to form a three-dimensional network, is an essential method for enhancing material properties. The application of this technique in ionic gel materials yields significant benefits. In 2020, Fazel Zare Bidoky *et al.* used photo-crosslinkable ionic gels and template-based screen printing to fabricate electrolyte-gated ZnO transistors [Fig. 3(e)]. The ionic gel consisted of a 1:9 weight ratio mixture of poly(styrene)-b-poly(ethylacrylate)-b-poly(styrene) (PS-PEtA-PS) triblock copolymer and the ionic liquid [EMI][TFSI] dissolved in ethyl acetate. This approach enhanced the ionic gel's resistivity and mitigated parasitic capacitance effects, resulting in faster device switching times.[106] Nevertheless, the practical application of this method may be limited due to certain constraints, as the photopolymerization technique requires specific environmental conditions. Improper control of factors such as light intensity and crosslinking time could result in incomplete crosslinking, thereby affecting the device's reproducibility. In 2023, Liu's team employed SnO_2 thin films as channels and designed a thermally crosslinked three-dimensional network to form the ionic gel layer, a mixture of [EMIM][TFSI] and cross-linkable solution. They developed a simple fabrication process for tunable ionic gels, reducing device power consumption to sub-femtojoule levels [Fig. 3(f)].[72] Moreover, combining ionic gels with oxides enables the fabrication of synaptic transistors with photoresponse behavior,[107, 108] and large-scale array fabrication can be realized through screen printing.[46, 109] Furthermore, incorporating the multi-gate structure into device design facilitates the development of multifunctional systems.[103, 110]

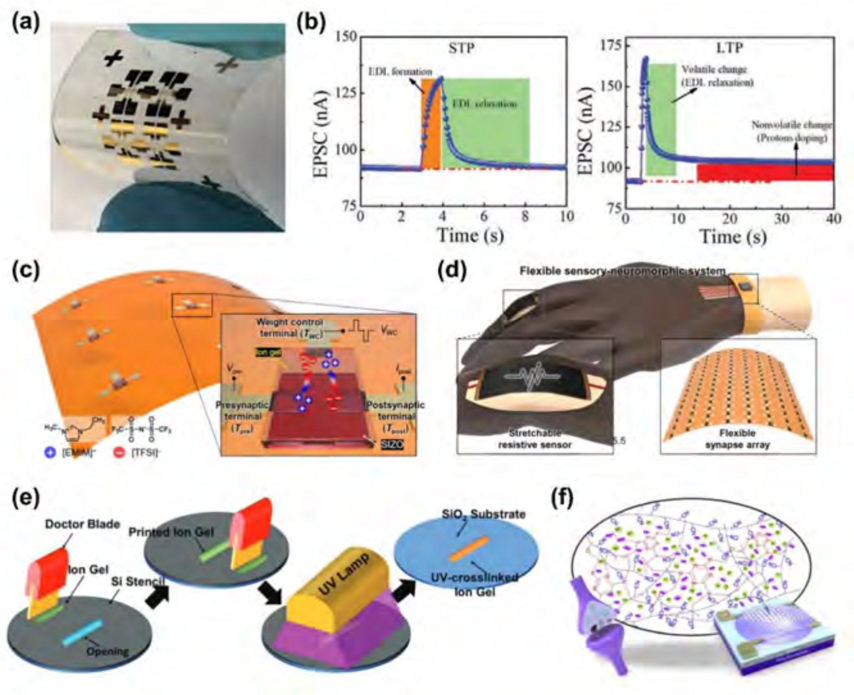

FIG. 3. (a) Optical image of the VO_2 IOSTs on a flexible mica substrate. (b) STP behavior under low gate voltage and LTP behavior under high gate voltage. Reproduced with permission from Deng *et al.*, Adv. Funct. Mater. **31**, 2101099 (2021).[101] Copyright 2021 John Wiley & Sons, Inc. (c) Schematic of the SIZO IOSTs based on UV-patterned [EMIM][TFSI] ionic gel. (d) Sensory neuromorphic system constructed from the IOSTs combined with stretchable resistive sensors, designed for sign language translation. Reproduced with permission from Oh *et al.*,

Sci. Adv. **7**, eabg9450 (2021).[102] Copyright 2021 American Association for the Advancement of Science. (e) Screen printing and UV crosslinking process of the ionic gel. Reproduced with permission from Bidoky *et al.*, Adv. Funct. Mater. **30**, 1902028 (2020).[106] Copyright 2020 John Wiley & Sons, Inc. (f) Thermally crosslinked ionic gel layer in an IOST. Reproduced with permission from Liu *et al.*, Chin. Chem. Lett. **34**, 107842 (2023).[72] Copyright 2023 Elsevier.

C. Organic-Polymer-Electrolyte-Mediated Oxide Synaptic Transistor

Organic polymer electrolytes are also commonly used dielectric material in IOSTs. Organic materials are characterized by simple synthesis methods, low cost, and excellent mechanical flexibility, allowing them to withstand mechanical deformations such as bending and stretching, thus ensuring compatibility with flexible substrates.

In most reported devices, the application of gate voltage may lead to the formation of conductive filaments or phase transitions at the interface. In contrast to these mechanisms, Bilge Yildiz's team designed an IOST with an optimized mechanism. The device utilizes WO_3 as the channel, PdH_x as the solid-state hydrogen storage layer and gate, and the organic polymer electrolyte Nafion-117 as the dielectric layer, which provides electronic insulation and proton conductivity [Fig. 4(a)]. Protons are inserted into the interconnected channels of the WO_3 lattice under the gate voltage control, where they combine with oxygen ions to form O-H-O defects [Fig. 4(b)]. The conductivity can be precisely modulated by adjusting the degree of proton insertion. This modulation mechanism differs from the conductive filament and phase transition mechanisms, offering excellent reversibility, linear conductance updates, and low power consumption [Fig. 4(c)].[80] The flexibility of organic polymer-based devices offers notable advantages. Min's team fabricates IGZO-based transparent flexible IOSTs on polyimide substrates using an organic polymer chitosan electrolyte and a high-k Ta_2O_5 thin-film as gate dielectric layer. The substrate is treated using a microwave annealing process, demonstrating stable electrical performance and mechanical integrity after 500 repeated bending cycles at a small bending diameter [Figs. 4(d) and 4(e)].[45] Furthermore, behaviors such as EPSC, PPF, multi-spike facilitation, and both potentiation and depression are successfully emulated. In addition to layered stacked devices, laterally coupled oxide-based transistors are also extensively studied [Fig. 4(f)],[111] contributing to the advancement of more compact and efficient neuromorphic system development. To enhance non-volatility, an ion-trapping layer can be incorporated into the electrolyte and channel to improve ion or charge adsorption.[112] Meanwhile, in response to environmental challenges, biodegradable biomaterials have gained attention. Researchers applied ion-tunable biomaterials with hydrophilic functional groups to

IOSTs, including chitosan,[111, 113] sodium alginate,[114, 115] starch,[116] konjac glucomannan (KGM) [Fig. 4(g)],[117] and natural gelatin.[118] Some of these devices can even dissolve in deionized water within a short time,[119] enabling environmentally friendly "artificial synapses" while reducing fabrication costs. Li *et al.* innovatively used natural biomaterial egg shell membrane (ESM) as the electrolyte to develop ITO transistors, with the entire fabrication process being simple and environmentally friendly.[120] However, batch-to-batch variations in natural materials and processing challenges may affect the consistency of the devices. Ding *et al.* fabricated IGZO IOSTs gated by a solid biopolymer electrolyte (SA/NH4Br) [Fig. 4(h)], where proton migration in the electrolyte induced counterclockwise hysteresis loops during gate voltage sweeps.[121] Most of these devices rely on proton modulation, offering advantages such as high sensitivity and low power consumption.[122] This paves the way for future neuromorphic applications inspired by green brain-inspired systems.

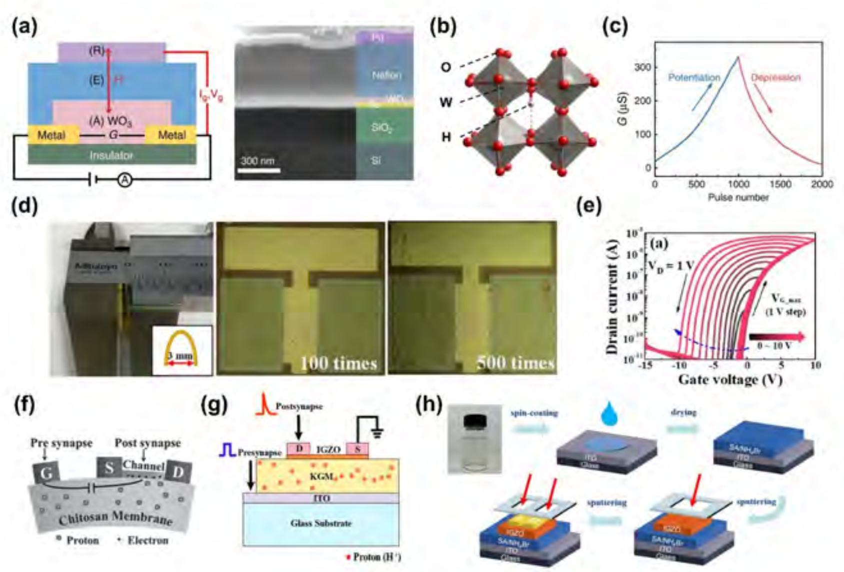

FIG. 4. (a) Schematic diagram and cross-sectional scanning image of the Nafion-117 organic polymer electrolyte transistor modulated by protons. Proton insertion sites between oxygen ions (b) and potentiation and depression behaviors of devices (c). Reproduced with permission from Yao *et al.*, Nat. Commun. **11**, 3134 (2020),[80] licensed under a Creative Commons Attribution (CC BY) license. Optical microscope images of flexible IOSTs with a bending diameter as small as 3 mm after 100 and 500 bending cycles (d), and gate voltage sweep results (e). Reproduced with permission from Min *et al.*, Molecules **26**, 7233 (2021),[45] licensed under a

Creative Commons Attribution (CC BY) license. (f) Schematic of a laterally coupled IZO transistor device. Reproduced with permission from Liu *et al.*, Adv. Mater. **27**, 5599 (2015).[111] Copyright 2015 John Wiley & Sons, Inc. (g) Schematic of IGZO IOSTs employing KGM organic polymer electrolyte. Reproduced with permission from Huang *et al.*, ACS Appl. Electron. Mater. **6**, 1521 (2024).[117] Copyright 2024 American Chemical Society. (h) Device fabrication flowchart of SA/NH4Br-gated IGZO IOSTs. Reproduced with permission from Ding *et al.*, J. Mater. Sci. **58**, 11740-11747 (2023).[121] Copyright 2023 Springer Nature.

D. Inorganic-Solid-Electrolyte-Mediated Oxide Synaptic Transistor

Inorganic solid electrolytes are widely used as dielectric layer materials in oxide transistors due to their high dielectric constant. IOSTs based on inorganic solid electrolytes allow for low operating voltages, excellent thermal stability, and chemical stability,[123] making them suitable for extreme environments such as high temperatures. Compared to other electrolyte materials, inorganic solid oxide transistors exhibit superior stability, durability, and reliable scalability for integration.[48, 76, 124] Moreover, the fabrication of inorganic solid oxide materials and thin films is more cost-effective and involves simpler processing techniques.

In inorganic solid oxide transistors, inorganic solid electrolytes are typically employed as gate dielectric layers, serving as ion donors and conduction channels. During ion conduction, the formation of conductive filaments can affect the controllability of the device. In 2020, A. Alec Talin's team reported that in resistive memory devices, the presence of nanofilaments leads to random switching. By introducing Y_2O_3-stabilized ZrO_2 (YSZ) as a solid electrolyte interlayer, filament formation can be eliminated, resulting in deterministic switching behavior [Fig. 5(a)].[125] However, Hyunsang Hwang's team suggested that in their WO_3-based IOSTs, oxygen vacancies in YSZ electrolyte promoted the growth of conductive filaments, facilitating linear switching and multilevel conductance modulation [Figs. 5(b) and 5(c)].[126] Consequently, although filaments can sometimes lead to unstable random switching behavior, they may also provide a richer modulation mechanism for conductance regulation in certain cases. The structure of solid electrolytes often provides fast ion conduction channels, enhancing the switching efficiency of the device. In 2021, Murat Onen *et al.* reported the first back-end CMOS-compatible proton-mediated non-volatile resistor, using phosphosilicate glass (PSG) as the dielectric layer and WO_3 as channel material. The porous structure of PSG ensures effective proton transport [Fig. 5(d)].[76] Additionally, the stability of solid-state inorganic electrolytes under harsh environments may make them the preferred choice. Recently, Philipp Langner *et al.* developed an all-solid-state IOST in their study, employing an oxide film, $Bi_2V_{0.9}Cu_{0.1}O_{5.35}$

(BICUVOX), which is compatible with CMOS technology, as the oxygen ion conductor electrolyte, and $La_{0.5}Sr_{0.5}FeO_{3-\delta}$ (δ = 0-0.25) as the channel material. Thanks to the high ionic mobility of the BICUVOX film, the device achieved stable oxide ion migration at low voltage (<1 V) and could reliably operate at 423.15 K.[127] Furthermore, IOSTs based on $NdNiO_3/SiO_2$ electrolytes, fabricated by Chadol Oh *et al.*, also demonstrated stable multilevel conductance modulation under low-voltage pulse control (⩾50 mV) at 423.15 K.[128] These research findings highlight the stability and high performance of inorganic-solid-electrolyte-mediated oxide synaptic transistors under low-voltage control, providing robust support for future low-power neuromorphic system research in high-temperature environments.[129] Nonetheless, when subjected to applications in ultra-high temperature environments (>600 K), the stability of the device still requires further investigation and optimization. Moreover, improving the compatibility of these devices with CMOS technology will significantly facilitate the large-scale deployment of this technology in practical applications and open possibilities for the realization of more complex integrated systems.[76, 77, 130]

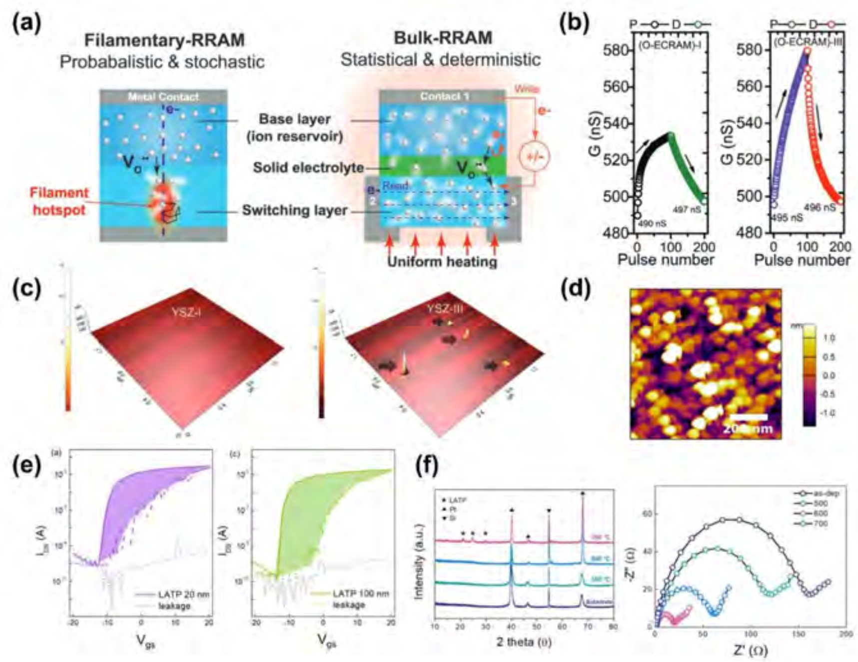

FIG. 5. (a) Schematic illustration of the internal switching mechanism of the device before and after the addition of the YSZ layer. Reproduced with permission from Li *et al.*, Adv. Mater. **32**, 2003984 (2020).[125] Copyright 2020 John Wiley & Sons, Inc. (b) The effect of oxygen vacancy

density in YSZ electrolyte (low in YSZ-I, high in YSZ-III) on synaptic potentiated or depressed weight update performance. (c) No conductive filaments form on the surface of YSZ-I, while several conductive filaments form on the surface of YSZ-III. Reproduced with permission from Nikam *et al.*, Adv. Electron. Mater. **7**, 2100142 (2021).[126] Copyright 2021 John Wiley & Sons, Inc. (d) Atomic force microscopy image of the PSG film surface. Reproduced with permission from Onen *et al.*, Nano Lett. **21**, 6111 (2021).[76] Copyright 2021 American Chemical Society. I-V curves of devices with 20 nm and 100 nm LATP dielectric layers under bidirectional gate voltage sweeps (e), and XRD patterns and electrochemical impedance spectra of the LATP dielectric layer annealed at different temperatures (f). Reproduced with permission from Park *et al.*, ACS Appl. Mater. Interfaces **15**, 47229 (2023).[131] Copyright 2023 American Chemical Society.

On the other hand, achieving an optimal solution requires comprehensive consideration of material parameters, structural design, fabrication costs, and process selection. In terms of fabrication, inorganic oxide films can be produced in large quantities and at low cost through methods such as chemical vapor deposition, physical vapor deposition, ALD, and sol-gel techniques.[132] To enhance the quality of film deposition and improve device performance, factors such as adjustable ion doping levels,[133] gas ratios during film deposition,[134] annealing conditions of the film,[135, 136] electrode materials,[137] and substrate surface treatments need also be considered. Additionally, annealing can optimize crystallinity and increase the on-state current and memory window,[4, 138-140] doping or plasma treatment to passivate dangling bonds and minimize interface trap density can improve the symmetry and linearity of weight updates,[67, 141, 142] reducing the ionic conductivity within the material can be used to improve the device's retention characteristics. [69, 143] Furthermore, factors such as film crystallographic orientation,[144] thickness,[145-147] size,[148, 149] and surface roughness play critical roles.[63, 150] For instance, surface roughness directly affects charge distribution at the interface, which in turn influences the electrical properties of the device. In 2023, Hyun-Suk Kim's team proposed an IOST based on $Li_{1-x}Al_xTi_{2-x}(PO_4)_3$ (LATP) inorganic solid electrolyte layer. They found that different film thicknesses impacted the hysteresis window width of the device [Fig. 5(e)], while varying annealing temperatures affected the crystallinity and conductivity of the LATP film [Fig. 5(f)].[131] Besides, in research on device fabrication, a well-designed device structure can optimize the electric field distribution and improve the response speed and stability of the device.[151, 152] Also, In addition to the technical parameters mentioned above, fabrication costs and manufacturing processes are also critical factors.[153, 154]

Table I summarizes the device information and performance parameters of IOSTs with different electrolyte materials as the dielectric layer. Each electrolyte material offers unique advantages in neuromorphic computing, making them suitable for various application requirements. Ionic liquids have high switching speed and ionic conductivity, but their volatility and environmental sensitivity limit their use in long-term stability and large-scale integration. Ionic gels and organic polymers offer excellent flexibility and biocompatibility; however, their relatively low mechanical strength and limited ionic conductivity may affect the durability and efficiency of devices in high-performance computing. In contrast, inorganic solid electrolytes show greater potential. Their outstanding chemical stability, mechanical strength, and high ionic conductivity not only ensure long-term reliability under harsh conditions but also facilitate integration with existing semiconductor processes. Therefore, due to their comprehensive performance advantages, inorganic solid electrolytes are more likely to become the mainstream electrolyte material choice in the future development of neuromorphic computing.

TABLE I. Summary of IOSTs, introducing dielectric layer and channel materials, mediated ions, size, synaptic performance and applications.

Dielectric Category	Dielectric Layer	Channel Layer	Ion	Channel size (L×W×T)	Operating voltage	On/off ratio	STP/ LTP	STDP	retention	PPF index	Linearity	Energy	Application Demonstration	Refs.
Ionic liquid	[DEME][TFSI]	WO_3	proton	500 μm×50 μm×30 nm	-2~2 V	20	S+L	Y	100 s	6.8%, Δt = 0.07 s		36 pJ	Image memorizing	49
Ionic liquid	[DEME][TFSI]	$SrCoO_x$	oxygen ions	210 μm×50 μm×20 nm	-2~2 V	60	L	Y	1 h				Image recognizing and memorizing, logic operations	81
Ionic liquid	[DEME][TFSI]	$La_{0.7}Sr_{0.3}MnO_3$	oxygen vacancies	1 mm×5 mm×6~7 u.c.	-2~1.5 V	>1	S+L	Y	500 s	70%, Δt = 5 s				97
Ionic liquid	[PMIM][TMS]	$SmNiO_3$	oxygen vacancies		-1~1 V	>1	L	Y	3 h					98
Ionic liquid	[DEME][TFSI]	CRFO	proton	1500 μm×150 μm×40 nm	-3.1~3 V	>1	L	Y						155
Ionic gel	P(VDF-HFP) + [EMIM][TFSI]	In_2O_3		80 μm×1600 μm×15 nm	-5~2 V	10^5							Adaptive artificial vision photoreceptor	46
Ionic gel	CEP + PMMF + [EMIM][TFSI]	SnO_2		48,400 μm×100 μm×75 nm			S			70%, Δt = 0.1 s		0.35 fJ	Logic operation, high-pass filtering	72
Ionic gel	PVDF-HFP + [DEME][BF4]	VO_2	proton	0.56 mm^2×40 nm	-3~3 V		S+L	Y		14%, Δt ≈ 160 s		0.88 pJ	Nociceptor, image recognition	101
Ionic gel	UV-patterned ionic gel	SIZO		30 μm×30 μm×30 nm	-20~20 V	>10^6	S+L						Sensory neuromorphic system, gesture recognition	102
Ionic gel	PS-PEtA-PS + [EMI][TFSI]	ZnO		200 μm×10 μm×50 nm	-2~2 V	>10^5							Inverter	106
Organic polymer electrolyte	Nafion-117	WO_3	proton	500 μm×100 μm×50 nm		30	L					18 aJ		80
Organic polymer electrolyte	Chitosan	IZO	proton	80 μm×1 mm×20 nm	-1.6~1.6 V	≈ 10^5	S+L			122%, Δt = 0.01 s		3.9 pJ	Logic operation	111

Organic polymer electrolyte	Chitosan	ITO	proton	80 μm × 1 mm × T	-1.5~1.5 V	$>10^6$	S+L	Y	30 s	27%, Δt = 0.02 s				[113]
Organic polymer electrolyte	Sodium alginate	ITO	SA ions	150 μm × 1 mm × 20 nm	-3~2 V	$>10^6$	S			17%, Δt = 0.01 s			Nociceptors	[114]
Organic polymer electrolyte	Konjac glucomannan	IGZO	proton	100 μm × 1 mm × 60 nm	-1.5~3 V	5.7×10^6	S			20%, Δt = 0.4 s		30 pJ	Image recognizing	[117]
Inorganic solid electrolyte	Li_3PO_4	WO_x	Li^+	5 μm × 5 μm × 50 nm	-2.5~3 V	6.4	L				0.60/-0.58		Pattern recognition	[64]
Inorganic solid electrolyte	AlO_x	InO_x	K^+	10 μm × 150 μm × 100 nm	-2~4 V	>10	S+L	Y	60 s	13%, Δt = 0.4 s		2.5 fJ	Image recognizing	[87]
Inorganic solid electrolyte	Yttria-stabilized hafnia	IGZO	H^+		-15~15 V	$>10^5$	L		300 s		0.949/-0.984	168.81 fJ	Pattern recognition	[143]
Inorganic solid electrolyte	$Li_{1-x}Al_xTi_{2-x}(PO_4)_3$	IGZO	Li^+	800 μm × 200 μm × 30 nm	-20~20 V	$\approx 10^6$	S+L				1.04/-2.22	2.7 nJ	Image recognizing	[131]
Inorganic solid electrolyte	LiPON	$Li_{1-x}CoO_2$	Li^+	2 μm × W × 120 nm			L		several weeks			1-10 aJ	Neural network simulation	[156]

IV. APPLICATION PROSPECT OF IOSTS

A. Multisensory Bionics

Biological systems possess the ability to sense and process multiple types of sensory information, such as vision, touch, hearing, and smell. These sensory inputs are transmitted and processed through complex neural networks, resulting in integrated perception. To replicate the multisensory functions of biological systems, electronic devices must be capable of processing diverse signals to perceive and respond to various environmental stimuli, while effectively coordinating, integrating, and outputting across different sensory channels.[157] Devices and systems based on IOSTs are able to mimic the functionality and dynamic characteristics of biological synapses, demonstrating remarkable potential in multisensory bionic systems.

1. Visual Perception

In the human sensory system, approximately 80% of external information is acquired through the visual perception system.[158] To achieve artificial visual biomimicry, IOSTs can utilize oxide layers with strong photoresponse as channels to respond to external light stimuli. Liu *et al.* demonstrated dual-mode modulation of a Li-doped AlO_x electrolyte-gated In_2O_3/ZnO IOST through both optical and electrical stimulation, and investigated the modulation of synaptic plasticity using light of different wavelengths, powers, durations, and intensities.[159] This suggests that by precisely controlling the light source parameters, synaptic plasticity can be flexibly modulated, thereby enhancing the responsiveness and adaptability of artificial visual systems. Additionally, different wavelengths can be combined to achieve dual-photonic gate control for all-optical configuration of weight updates. This is attributed to the optoelectronic gating effect provided by the photo-generated electrons trapped in Al_2O_3 under infrared light and the ionized oxygen vacancies in In_2O_3 under ultraviolet light.[160] Moreover, expanding single optoelectronic devices into device arrays to build neuromorphic computing architectures facilitates efficient parallel information processing and multifunctional integration. Qiu *et al.* combined an ionic gel (P(VDF-HPF) + [EMI][TFSA]) and Al_2O_3 as gate-stacked dielectrics with an IGZO channel to trap photo-generated charges at the channel/ionic gel interface, creating an artificial vision system based on an artificial retina array (ARA) and ANNs. The ARA, consisting of 784 IGZO transistors, can be used for image pre-processing to eliminate background noise, while an ANN based on a single-layer perceptron performs image training and recognition functions [Fig. 6(a)].[161] Furthermore, adaptive behavior is a critical feature of biological visual systems, allowing the human eye to adjust and adapt to complex and dynamic environments.[162] Jin *et al.* fabricated an In_2O_3 phototransistor array with negative photoconductance behavior using ionic gel (P(VDF-HFP) + [EMIM][TFSI]) prepared by screen printing, achieving an artificial vision perception system capable of simulating brightness adaptation [Fig. 6(b)].[46] In addition to processing visual information, human visual neurons also function as memory units. Similarly, artificial vision systems can perform feature extraction, image recognition, and memory functions.[163-165]

2. Tactile Perception

Moreover, tactile perception is a key biomimetic technology. By applying piezoelectric and flexible materials, the tactile perception of human skin can be mimicked, which can drive the development of intelligent robotics, wearable devices, and human-machine interaction.[166] Zhang *et al.* reported a stable, flexible ITO IOST using an ionic gel consisting of blending polymer (P(VDF-HFP)), ionic liquid [EMI][TSFA]), and acetone. When combined with an external thin-film pressure sensor, it enabled tactile sensing for braille code recognition.[167] In addition, IOSTs may also be used for movement direction detection. In the 5×5 array of IOSTs, the tactile-triggered spike current is received by the device array, and after being processed by the constructed spiking neural networks (SNNs), the touch direction can be intelligently identified [Fig. 6(c)].[168] Similarly, nociceptors that mimic pain receptors have been successfully simulated, demonstrating key features such as threshold detection, relaxation, and sensitization, along with graded pain perception.[101] Li *et al.* emulated human nociceptors using a sodium alginate biopolymer electrolyte-gated ITO IOST transistor array. Their system showed weak responses to sub-threshold or short-duration stimuli, while exhibiting significant perception to stimuli that exceeded a certain threshold or duration, mimicking the mechanism of biological nociceptors [Fig. 6(d)].[114] Furthermore, the integration of IOSTs with triboelectric nanogenerators has enabled the simulation of fear neural circuits, providing early warning signals for integrated systems.[169]

3. Auditory Perception

Bionic auditory perception is also a promising area of research. In bionic auditory systems, sound localization is achieved by mimicking the biological process of perceiving and judging the direction and distance of sound, which has significant implications for spatial awareness, navigation, human-machine interaction, and security monitoring. He *et al.* developed a pair of chitosan electrolyte-gated IGZO IOSTs to detect sound azimuth. Two gate terminals and two pairs of source-drain terminals were designated as PREN1/PREN2 and POSTN1/POSTN2 [Fig. 6(e)]. By simulating the interaural time difference in biological systems, two stimulus signals applied at different times are introduced to PREN1 and PREN2. The function of the time delay between the stimulus signals and the sound azimuth is shown in Fig. 6(f).[170] This work achieves precise sound source localization based on IOST devices, demonstrating the potential of IOSTs in biomimetic auditory systems. The typical audible frequency range for the human ear spans from 20 Hz to 20 kHz. Therefore, the operating frequency of acoustic response devices should be optimized to cover this range.[171]

Additionally, biomimetic systems for olfaction,[172] and gustation have been studied.[173] Integrating these biomimetic devices will enable the simultaneous perception of multiple environmental stimuli. This will facilitate the development of more intelligent multisensory systems.

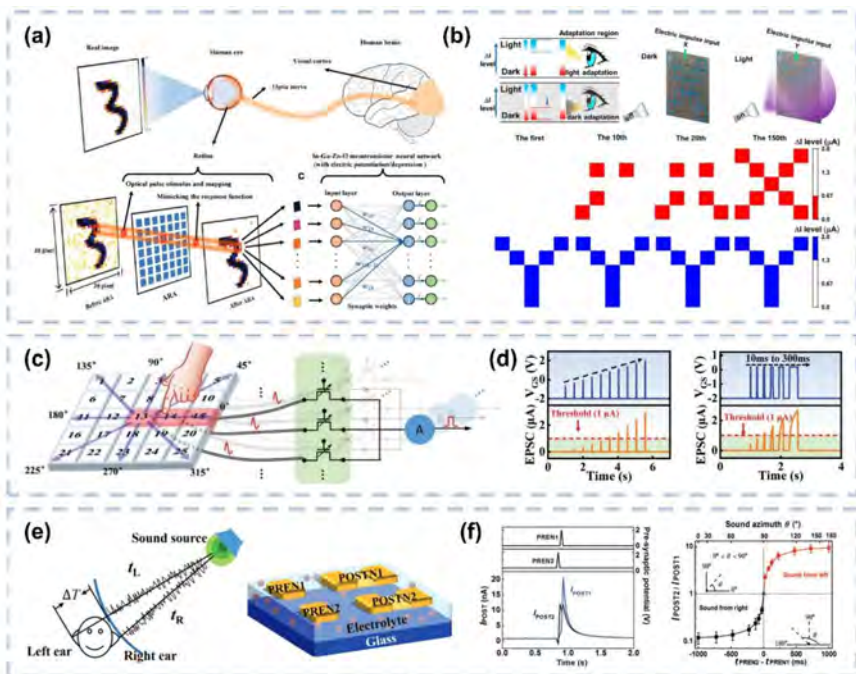

FIG. 6. (a) The ARA simulated by 784 IGZO IOSTs filters the noise from handwritten images, and then sends them to the ANN for training and recognition. Reproduced with permission from Qiu *et al.*, Adv. Funct. Mater. **30**, 2002325 (2020).[161] Copyright 2020 John Wiley & Sons, Inc. (b) In_2O_3 IOSTs array based on ionic gel, which used for adaptive artificial vision perception. Input of "X" image in the dark and "Y" image in the light using electrical pulses, with the "X" or "Y" image formed after the 1st, 10th, 20th, and 150th pulse. Reproduced with permission from Jin *et al.*, Nano Lett. **22**, 3372 (2022).[46] Copyright 2022 American Chemical Society. (c) An array of IOSTs used for motion direction detection. Reproduced with permission from Li *et al.*, Adv. Mater. **32**, 2003018 (2020).[168] Copyright 2020 John Wiley & Sons, Inc. (d) As the pulse amplitude and width increase beyond a certain threshold, the non-pain response

transitions to a pain perception event. Reproduced with permission from Li *et al*., Nanoscale **14**, 2316 (2022).[114] Copyright 2022 Royal Society of Chemistry. (e) A pair of IOSTs simulating binaural hearing, enabling sound localization. (f) The function of the time interval between stimulus signals and the sound azimuth. Reproduced with permission from He *et al*., Adv. Mater. **31**, 1900903 (2019).[170] Copyright 2019 John Wiley & Sons, Inc.

B. Neuromorphic Computing

1. IOSTs-based Artificial Neural Networks

ANNs are computational models designed to mimic the interactions between neurons in the biological brain. They consist of numerous nodes, commonly referred to as "neurons," which interact through connections with varying weights. Neural networks are typically organized into three layers: the input layer, the hidden layer(s), and the output layer. The input layer receives external data, the hidden layer(s) perform complex nonlinear transformations on the data, and the output layer provides the final prediction or classification outcome. Based on differences in connectivity structure and computational mechanisms, ANNs encompass various types of network architectures, primarily including convolutional neural networks (CNNs), recurrent neural networks (RNNs), and SNNs.[174] Among them, CNNs excel at processing spatial data (such as images), RNNs are well-suited for handling temporal data (such as speech and text), while SNNs, by simulating the spiking mechanism of biological neurons, more closely replicate the dynamic behavior of biological neural networks. Traditional ANNs are typically implemented in software; however, due to the significant energy consumption and limited physical space, researchers have started exploring hardware-based implementations of ANNs—directly using electronic devices to simulate the computational processes of neural networks. By structuring the IOSTs into a crossbar array, each crosspoint represents a weight, with these weights expressed by conductance values. Based on Ohm's law and Kirchhoff's law, input signals (voltage vectors) are converted into output signals (current) through these weights (conductance matrix). This process directly corresponds to the weighted summation step in neural networks, allowing the computation to be executed directly at the hardware level.[73]

Due to their high stability and low power consumption, hardware crossbar arrays based on IOSTs are frequently applied in pattern recognition tasks such as image recognition.[175, 176] In neural network simulations, optimizing the synaptic performance in the device enhances the accuracy of the weighted summation operation.[43, 74] Jin's team significantly improved synaptic characteristics of IGZO IOSTs by optimizing the yttrium concentration (Y8.03) in the HfO_2 solid-state electrolyte, including the linearity and symmetry of weight updates, the number of weight states, and the ratio of maximum to minimum conductance. Using this optimized configuration, they constructed a three-layer ANN and performed pattern recognition simulations for the digit '3' using the modified National Institute of Standards and Technology (MNIST) dataset, achieving an accuracy of 94%, which is significantly higher than the 84% accuracy of Y1.74 [Fig. 7(b)].[143] Additionally, to enhance interface stability, Nikam *et al.* inserted a graphene interlayer at the PVA/$LiClO_4$ electrolyte-WO_3 channel interface, resulting in the device that exhibited nearly linear conductance switching and non-volatile multi-level conductive states. Based on this, they simulated the MNIST handwritten dataset, with the input, first hidden, second hidden, and output layers consisting of 780, 250, 125, and 10 neurons, respectively. The results showed that the graphene interlayer improved the device's recognition rate from 79.18% to 93.26%.[68] Moreover, neural network models based on IOSTs are capable of not only image recognition but also dynamic pattern image memory.[47]

Meanwhile, inspired by the biological spiking mechanism, SNNs perform dynamic information processing and computation in an event-driven manner, characterized by high temporal resolution and low energy consumption. Li *et al.* employed IOSTs with amorphous Nb_2O_5 as the channel material and Li_xSiO_2 as the electrolyte gate material, constructing a 32× 32 device array and developing an SNN with spatiotemporal information processing [Fig. 7(a)].[168] Subsequently, the group combined one of the fabricated IOSTs with a transistor to form a synaptic device, which reduced the self-discharge of the IOST device. Based on this, an SNN was designed for associative memory tasks, demonstrating the ability to learn and robustly reconstruct images of handwritten digits.[177] This demonstrates that diversified device integration and optimization can effectively enhance the application potential of SNNs in pattern recognition and memory tasks. Also, static logic computation and dynamic logic functions have also been extensively studied.[81] Static logic computation performs simple logical operations, such as 'OR,' 'AND,' 'NOR,' and 'NAND,' through fixed weights and structures.[178] In contrast, dynamic logic involves time-varying inputs and states, similar to time-dependent computations in ANNs.[65, 165] In addition, to better emulate the dynamic behavior of biological neural systems, high-pass filtering can be used to enhance specific frequency components, enabling ANNs to more effectively recognize inputs with these characteristics.[82, 179]

2. IOSTs-based Reservoir Computing

Recently, reservoir computing (RC) has become a research hotspot.[180-182] In RC, the reservoir is a dynamic system composed of an input layer, the reservoir itself, and an output layer.[183] The reservoir contains a large number of random, fixed nonlinear nodes, and its internal structure and connection weights remain unchanged during training, with only the output layer's weights being trained.[184] Due to its lower training cost, RC is highly efficient in handling complex temporal tasks, making it suitable for pattern recognition and classification. Yang *et al.* employed a time-division multiplexing mask technique based on ion relaxation, utilizing the STP of the proposed IGZO IOSTs with SiO_2 electrolyte gating to realize a dual-layer reservoir system [Figs. 7(c) and 7(d)]. Furthermore, they simulated the recognition of handwritten digits and spoken digit signals, achieving recognition accuracies of 90.86% and 100%, respectively, with an energy consumption as low as 1.86 nJ.[185] In 2024, Liu's team proposed a multi-terminal ScO_x electrolyte-gated ITO IOST that combines electrostatic control and electrochemical doping mechanisms. By leveraging the volatile and non-volatile dynamics of IOSTs, they successfully simulated synaptic functionalities of STP and LTP. Additionally, tasks under different input modes were effectively managed, with signal processing in the reservoir enabled by the nonlinear response and volatile modulation, and in-memory computing of the readout network achieved via the non-volatile electrochemical doping mechanism [Fig. 7(e)].[186] Consequently, a physical RC system was realized using only a single IOST, which was subsequently applied to image recognition. This highlights the flexibility and efficiency of IOSTs in reservoir computing and neural network simulation. Time-delayed reservoir computing (TDRC) is a variant of RC, where the reservoir is constructed by introducing time-delayed feedback. It consists of nonlinear nodes and delay loops, offering simple hardware implementation and suitability for real-time signal processing. Fang's group developed oxygen-mediated IOSTs with a TaO_x electrolyte/α-IGZO channel, and based on the rich dynamic characteristics of the device, they constructed a TDRC system capable of waveform classification and handwritten digit recognition.[187] Building on this, the group created three common-gate IOSTs with different channel lengths. The current responses of channels with varying lengths help supplement computational resources and improve accuracy. As a result, a deep TDRC was developed to perform tasks such as speech digit classification and Hénon map prediction, achieving excellent performance with high accuracy (≈ 92.2%) and ultra-low normalized root mean square error (≈ 0.013).[188]

Overall, IOST-based ANNs and RCs demonstrate significant potential in complex data processing and intelligent sensing. However, issues such as their long-term stability, scalability, and adaptability in complex environments still require further optimization and validation to ensure their full performance in practical applications.

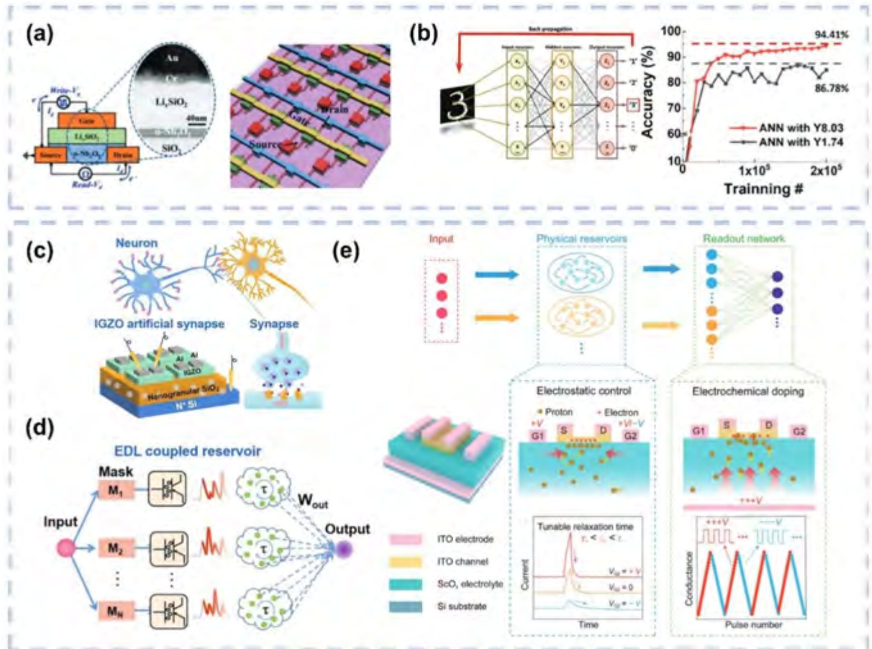

FIG. 7. (a) Schematic diagram of the device structure, cross-sectional electron microscope image, and 32×32 array layout. Reproduced with permission from Li *et al.*, Adv. Mater. **32**, 2003018 (2020).[168] Copyright 2020 John Wiley & Sons, Inc. (b) Schematic of the device integrated into an ANN, where the Y8.03-based IOSTs demonstrates a higher pattern recognition accuracy of 94.41%. Reproduced with permission from Jin *et al.*, Small **20**, 2309467 (2024).[143] Copyright 2024 John Wiley & Sons, Inc. (c) Schematic illustration of biological neurons, synapses, and the IGZO IOST structure. (d) Schematic diagram of a conventional RC system. Reproduced from Yang *et al.*, Appl. Phys. Lett. **122**, 043508 (2023),[185] with the permission of AIP Publishing. (e) Schematic of the ITO IOST device structure and its internal mechanisms applied to different tasks. Reproduced with permission from Liu *et al.*, Nano Res. **17**, 4444 (2024).[186] Copyright 2024 Springer Nature.

V. PROSPECTS AND CHALLENGES

Despite the significant potential of IOSTs across various application fields, several challenges still require further investigation and resolution.

First, the defects and control of oxide materials. The control of oxygen vacancies and defects within oxide materials used as channel layers remains a challenging task. Oxygen vacancies are randomly formed during the fabrication of thin films, and their formation, distribution, and concentration are difficult to precisely mediate. Various fabrication methods, conditions, and environments can lead to random distributions of oxygen vacancies, affecting the reproducibility and stability of material performance. To address these issues, precise control of oxide thin-film deposition conditions is crucial for adjusting the material's stoichiometry,[64-67] which significantly impacts carrier concentration and the density of oxygen vacancy defect states. Additionally, annealing is a key technique for optimizing oxide crystallinity and minimizing interface defects. Moreover, reactive metals can effectively modulate oxygen defects. By reacting oxide materials with reactive metals such as lithium, sodium, or calcium, oxygen atoms can be removed, leading to the formation of more oxygen vacancies within the oxide lattice [Fig. 8(a)].[189]

Secondly, there are issues related to ionic conductivity and durability. One of the key properties of electrolyte materials used as dielectric layers is ionic conductivity, yet the uniformity of ion migration and durability remain significant challenges. During the deposition process of thin films, factors such as temperature, humidity, and atmospheric conditions can cause uneven distribution of ions within the dielectric layer. Over extended operation periods, the cumulative effects of ion migration may lead to the degradation of dielectric layer performance, thereby affecting the memory characteristics and durability of the device. To address this issue, researchers should focus on optimizing or designing new composite electrolyte materials or multilayer structures to extend their lifespan, such as ceramic materials or multilayer design approaches.

Again, the modulation speed of IOSTs needs to be significantly improved to meet the demands of large-scale, high-speed computing. Ion migration occurs within the dielectric layer under electric fields or chemical gradients. Compared to electrons and holes, ions have larger masses and are more likely to be trapped or scattered by lattice defects during migration, resulting in lower migration efficiency. However, IOSTs rely on processes such as ion accumulation, diffusion, or injection to function, leading to longer response times. This remains behind the picosecond (ps) switching speeds achieved by memristors and plasmonic nano-switches.[190, 191] This makes real-time computation and training of deep neural networks particularly challenging, as ANNs typically require rapid updates and optimization of weights. To address this, materials can be designed with porous structures, fabricated into ultrathin films, and reduced in channel size to shorten ion diffusion paths. Additionally, the quality of film deposition is critical. Well-ordered single-crystal films can reduce lattice dispersion during ion transport, and enhance migration efficiency. Furthermore, substituting elements to weaken the interaction forces between ions and their surrounding bonds can also improve ion transport and increase modulation speed [Fig. 8(b)].[63]

In addition, when facing more complex extreme application scenarios such as wide temperature ranges, high humidity, and strong radiation, the stability of IOSTs becomes crucial. For example, in high-temperature environments, the ionic mobility of ion-conducting materials increases significantly. While this can accelerate the device's response speed, the mismatch in thermal expansion coefficients at the interface may lead to instability or even failure of the device. Currently, to the best of our knowledge, reports on IOSTs show a maximum tolerance temperature of only around 420 K, [127, 128] while ultra-high thermal resistance above 600 K has mostly been reported in studies based on two-dimensional and ferroelectric materials.[86, 192, 193] Nevertheless, oxide materials possess inherent stability, and through the selection of appropriate inorganic solid-state electrolytes and the implementation of certain optimization techniques, there remains significant potential for achieving ultra-high-temperature stability.

Moreover, in terms of integration and applications in neuromorphic computing, IOSTs still have a long way to go. Large-scale integration and chip fabrication are inevitable trends for neuromorphic devices. As early as 2013, Qualcomm released the "Zeroth" processor, aimed at simulating brain architectures to achieve more efficient information processing. In 2014, International Business Machines Corporation, under the U.S. Defense Advanced Research Projects Agency program, successfully developed a neuromorphic chip called "TrueNorth".[194] This chip features 1 million electronic neurons and 256 million electronic synapses, making it suitable for real-time neural network applications. On April 17, 2024, Intel announced the development of the world's largest neuromorphic system "Hala Point", which integrates processing, memory, and communication pathways into a massively parallel architecture. When running all 1.15 billion neurons, "Hala Point" can achieve processing speeds 20 times faster than the human brain. These cutting-edge neuromorphic chips are primarily based on CMOS technology. While IOSTs discussed in this paper offer superior advantages in mimicking biological neurons and synapses,[195] they are still a considerable distance from large-scale commercial application. Achieving high-yield, stable-performance large-scale IOSTs arrays and chips remains a challenge that requires further exploration and innovation [Fig. 8(c)].[11] IOSTs based on liquid dielectric layers do not have an advantage in this regard. IOSTs with inorganic solid-state electrolytes compatible with CMOS fabrication processes may be the best choice. Furthermore, by employing 3D integrated circuit technology to stack multiple IOSTs, it is possible to maximize node density and interlayer connections, significantly improving the device's integration.[183] Furthermore, Figs. 8(d)-8(f) illustrate several promising future applications for IOSTs, including bio-inspired multi-sensory robots [Fig. 8(d)], wearable health monitoring devices [Fig. 8(e)] and human-machine interfaces [Fig 8(f)].[58] These forward-looking intelligent applications are expected to serve as key building blocks in next-generation smart computing systems.

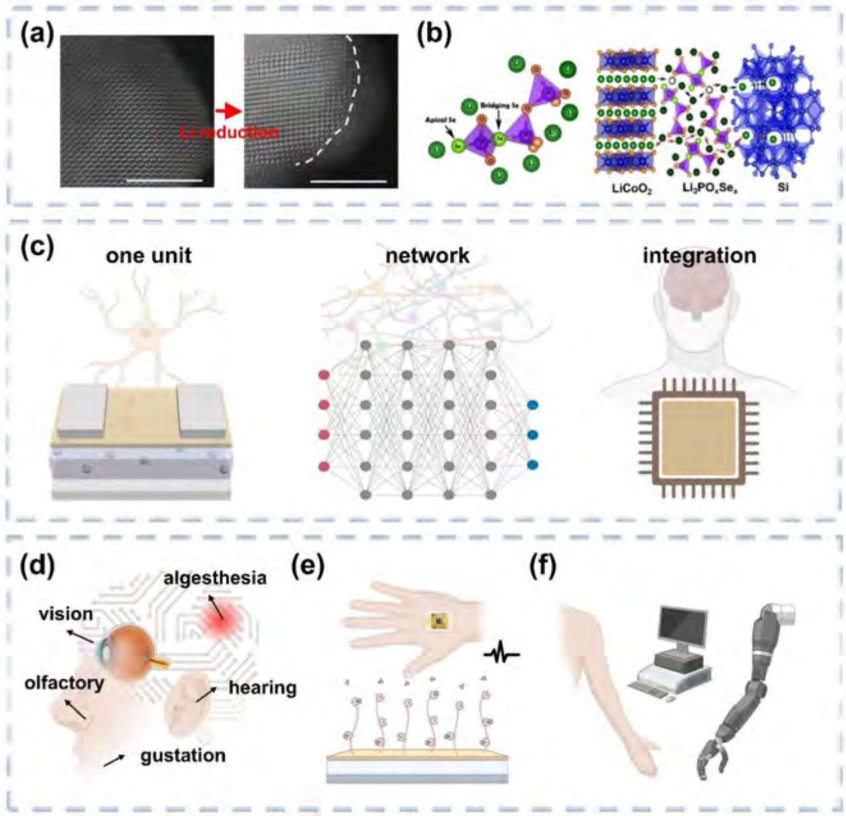

FIG. 8. Optimization strategies and promising applications for IOSTs. (a) Transmission electron microscopy (TEM) images of pristine TiO_2 and 5% Li-reduced TiO_2 show a transition from ordered to partially disordered surface crystal domains, indicating that Li effectively mediates oxygen vacancies in TiO_2. Reproduced with permission from Ou *et al.*, Nat. Commun. **9**, 1302 (2018),[189] licensed under a Creative Commons Attribution (CC BY) license. (b) The structural model of $Li_3PO_xSe_x$ electrolyte, formed by Se substitution of Li_3PO_4, and a schematic of the ionic switching dynamics demonstrate that Se substitution facilitates ion migration, leading to faster modulation speeds. Reproduced with permission from Nikam *et al.*, Sci. Rep. **9**, 18883 (2019),[63] licensed under a Creative Commons Attribution (CC BY) license. (c) A

complete development process of a neuromorphic architecture is illustrated, from individual units and multi-unit networks to integrated chips. Prospective applications of IOSTs include bionic multi-sensory robots (d), wearable health monitoring devices (e), and human-machine interaction (f). (c)-(f) were created in BioRender.

VI. SUMMARY

This review introduces the biomimetic advantages of IOSTs by comparing them with biological synapses, highlighting key parameters that are generally considered in related research. Then we discuss the use of various electrolyte materials with unique advantages as dielectric layers in IOSTs, elaborating on the internal mediation mechanisms and common optimization strategies of the devices. Last but not least, we review the latest advancements of IOSTs across different fields, and discuss the challenges and prospects in material defect control, durability, modulation speed, environmental stability, and large-scale integration. Through further exploration and optimization of materials, thin films, and device architectures, IOST is poised to address the complex challenges faced by modern computing. It is expected that IOSTs will play a key role in advancing low-power, high-efficiency neuromorphic computing technologies.

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AUTHOR DECLARATIONS

Conflict of Interest Statement

The authors have no conflicts to disclose.

Author Contributions

Ruihai Li: Data curation (lead); Formal analysis (equal); Investigation (equal); Visualization (equal); Writing – original draft (lead). **Liuqi Cheng:** Formal analysis (equal); Methodology (equal). **Wanrong Liu:** Investigation (equal); Writing – original draft (supporting). **Chenxing Jin:** Methodology (equal); Resources (supporting). **Xiaofang Shi:** Data curation (supporting); Visualization (equal). **Pengshan Xie:** Resources (equal); Visualization (equal). **Qijun Sun:** Formal analysis (equal); Project Administration (equal); Writing – review & editing (equal). **Mengqiu Long:** Methodology (equal); Resources (equal); Supervision (equal). **Junliang Yang:** Funding acquisition (equal); Resources (equal). **Johnny C. Ho:** Formal analysis (equal); Supervision (equal). **Jia Sun:** Conceptualization (lead); Funding acquisition (equal); Project Administration (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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