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Nanofluidic systems for ionic intelligence

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Artificial intelligence is rapidly permeating modern technology, but its growth is increasingly constrained by the costs of delivering power and removing heat. Neural computation offers a striking counterpoint, for it achieves sophisticated information processing at exceptionally low energy by exploiting ionic flows and adaptive conductance. Inspired by the Hodgkin–Huxley view that function emerges from ion-transport dynamics, recent work has begun to implement memory and learning directly in fluids, where ions simultaneously carry signals and encode the internal device state. This Review charts the emerging landscape of fluidic ionic memristors, from soft, bioinspired materials to manufacturable solid-state nanofluidic architectures. In lipid bilayers, droplet networks, tissues and ionic polymers, electrical activity is intrinsically coupled to chemistry and mechanics, enabling plasticity across multiple timescales. In rigid nanopores, nanochannels and angstrom-scale slits, the softness is transferred from the scaffold to the ionic degrees of freedom, where electric double-layer dynamics, concentration polarization and confinement-driven effects produce history-dependent transport in robust inorganic frameworks. Hybrid approaches integrate gels, brushes, particles, or biomolecules within microfabricated structures to combine stability with rich analogue dynamics. We conclude by outlining the key requirements for translation from reproducibility to scalable integration towards ionic intelligence technologies.

1. Introduction

Artificial intelligence is becoming an always-present layer of the internet, yet its rapid expansion is now limited as much by physical constraints as by advances in algorithms. As large language models are trained and deployed at scale, computation is concentrated in dense accelerators and data centers, where increasing heat fluxes, cooling burdens and the life-cycle footprint of electricity now pose major sustainability constraints.[1–3] This backdrop has renewed interest in neuromorphic computing,[4] which pursues brain-like learning and inference through sparse, event-driven signalling rather than the clocked von Neumann architecture. In the Hodgkin–Huxley picture, such computation is performed by voltage- and time-dependent ionic conductance whose internal ionic states store history and govern dynamics, a design principle that inspires ionic intelligence hardware in which ions, rather than electrons, carry signals and encode memory.[5–8] Drawing on these biological principles, scientists have sought to create nanofluidic memristors, artificial two-terminal devices in which ion transport under confinement exhibits history-dependent conductance analogous to synapses.[9–14] Over the past decade, this emerging class of iontronic devices has rapidly emerged as a bridge between living neural networks and semiconductor processors, aiming to emulate brain-like learning and memory with the very same carriers of information used in biology.

Early ionic memristors have already captured many canonical synaptic functions while operating at exceptionally low power.[15] Current transients in nanofluidic channels can

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consume only femtojoules per spike,[16] placing them close to the efficiency of biological synapses.[16–18] Fluidic memristors also share a closer physical analogy with natural synapses than conventional solid-state devices, because they function in water with mobile ions and solvent molecules as active components of transport. This chemically rich environment, together with the multispecies character of ionic carriers, their hydration shells, valence states and reversible binding, enables dynamical behaviors that are inaccessible to purely electronic systems. As a result, ion-driven memristors have begun to reproduce

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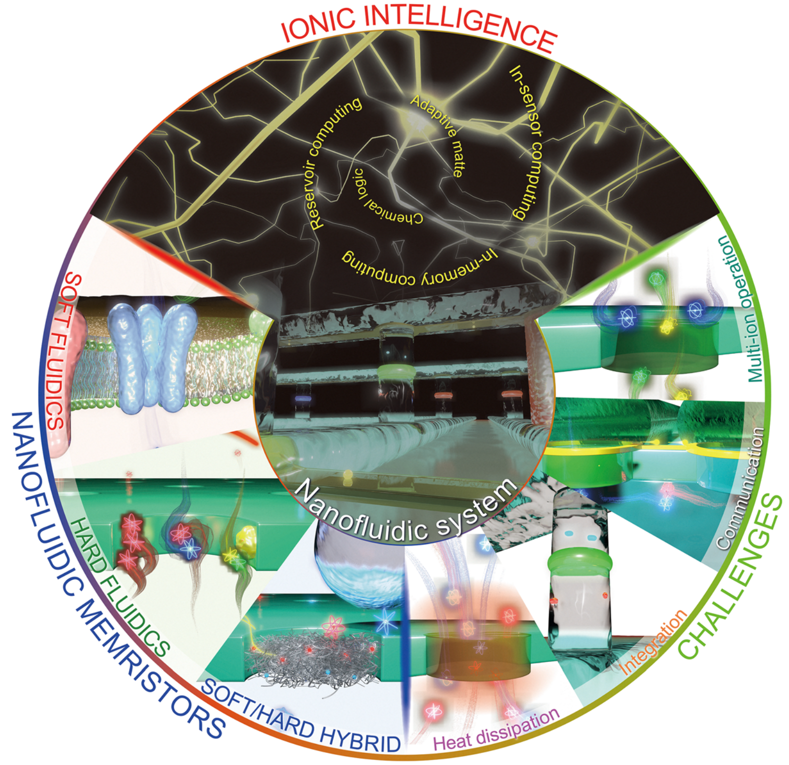

Fig. 1 Conceptual diagram summarizing the central theme of this Review: confined ion transport can generate memory and computation when coupled to slowly evolving internal states.

short-term plasticity,[19] long-term plasticity,[20] spike-timing-dependent plasticity,[21] and even higher-order learning-forgetting dynamics,[22] highlighting their distinctive potential for neuromorphic engineering.

Yet, substantial challenges still separate nanofluidic memristors from their full potential (Fig. 1). Reproducing the ion-selective, multi-ion operation of real neurons and glia remains a central unsolved problem. Devices capable of exploiting several ionic species in parallel, analogous to the distinct signaling roles of Na^+, K^+ and Ca^{2+} in biology, have yet to be realized for complex information processing. Scaling fluidic memristors into large iontronic circuits presents a further obstacle, because such systems are intrinsically more difficult to address, interconnect and control than solid-state counterparts. Even so, the field has begun to make important progress, with early demonstrations of logic operations and neural-network computation using small numbers of ionic memristors.[23] As attention shifts towards larger-scale hardware, hybrid architectures that combine rigid nanochannels with soft polymers or hydrogels are emerging as a promising route to unite structural robustness with adaptive ionic functionality.

This Review surveys the rapidly expanding landscape of nanofluidic memristors for artificial intelligence, focusing on ion transport rather than electron conduction as the basis of operation. We cover hard fluidic platforms built from solid-state nanochannels and nanopores, soft ionic media including biomembranes, droplets and polymer matrices, and hybrid architectures that combine these approaches (Fig. 2). Throughout, we emphasize how ionic dynamics, ranging from slow

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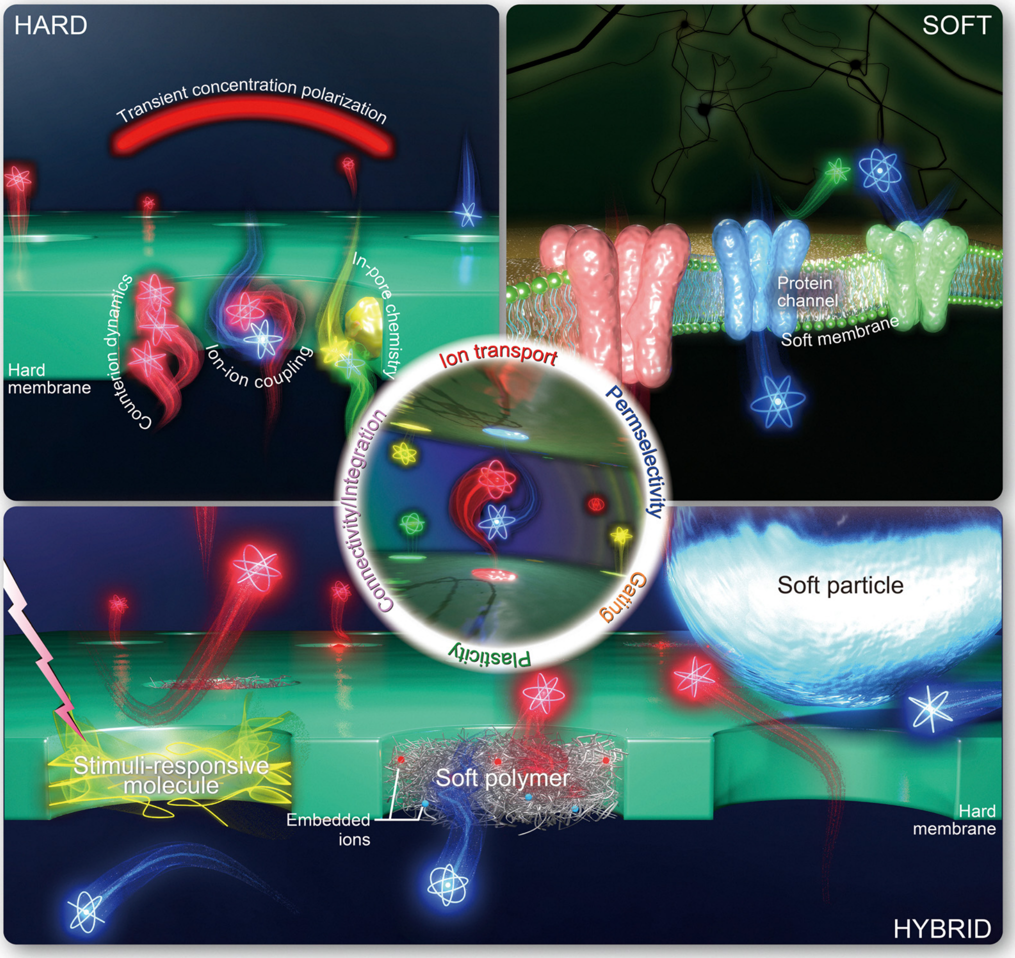

Fig. 2 Soft, hard, and hybrid nanofluidic platforms for ionic intelligence. Conceptual map of how ionic memory and computation emerge when ion transport is confined and made state dependent. Hard systems (top left) use rigid membranes and engineered nanochannels, where history dependence arises from slow counter-ion relaxation, ion–ion correlations and in-pore chemistry, often expressed through transient concentration polarization. Soft systems (top right) rely on compliant membranes and biomolecular pores, in which the ionic flux is inseparable from conformational and mechanical degrees of freedom. Hybrid systems (bottom) integrate a manufacturable hard scaffold with soft functional elements to enable reconfigurable gating and multiscale plasticity. The central inset highlights shared functional primitives in the form of an ionic circuit in an artificial nanofluidic network.

counterion accumulation to fast electrowetting at nanoscopic interfaces, generate memristive behaviour. We highlight key mechanisms including electric-double-layer hysteresis, ångström-scale confinement, electrohydrodynamic flow memristors, optically modulated ionic transport and chemical memory in nanopores. We then examine emerging multi-memristor circuits, including ionic logic gates and synaptic networks, to show how such devices can perform computation. Finally, we discuss the major challenges ahead, including thermal management and scalable integration. Our aim is to provide a timely and comprehensive perspective on nanofluidic memristors, and to clarify both the remarkable progress towards fluid-based artificial synapses and the remaining path to fully ionic intelligent systems that compute with brain-like efficiency and elegance.

To refine this conceptual framework, we move beyond a purely materials-based soft/hard/hybrid categorization and instead organize the field around four recurring physical mechanisms: electric-double-layer charging and relaxation, concentration polarization and diffusive redistribution, electrochemical reactions coupled to interfacial ion adsorption, and mechano-ionic coupling arising from structural compliance. This mechanism-centered view makes it easier to compare otherwise disparate platforms on common physical grounds and to connect device physics directly to function, including short-term plasticity, long-term retention, spiking and adaptive learning. Soft lipid bilayers and hydrogels, for example, draw primarily on interfacial charging and electrochemical doping, whereas rigid nanochannels intensify diffusion, adsorption and correlation effects under extreme confinement. Hybrid systems are best understood as deliberate combinations of these mechanisms, assembled to balance programmability, robustness and scalability.

These platforms are therefore best viewed not as discrete categories, but as a design continuum. In soft fluidics, the state variable resides in reconfigurable matter itself, such as membranes, droplets, polymer networks and living tissues, so memory is inseparable from compliance, chemical binding and slow ionic relaxation. Hard nanofluidic systems retain the same ionic carriers and aqueous transport physics, but confine them within rigid nanopores and nanochannels, shifting plasticity from mechanical deformation to interfacial charge, hydration and reaction landscapes defined by an inorganic scaffold. Hybrid architectures occupy the intermediate regime, preserving the addressability, reproducibility and lithographic precision of hard nanofluidics while reintroducing soft internal degrees of freedom through gels, brushes, biomolecules or confined liquid phases. Conventional solid-state memristors sit adjacent to, rather than within, this fluidic continuum. They likewise encode memory through delayed internal-state evolution, but the relevant variables are typically electronic, lattice-ionic or defect-based configurations rather than a mobile aqueous ionic population. Framed in this way, the comparison highlights both the shared logic of history-dependent transport and the distinct physical substrates that each platform brings to adaptive computing.

2. Soft fluidic platform

We begin with soft fluidic platforms, where compliance, hydration, and molecular rearrangement are not merely structural attributes but active parts of the memory mechanism.

The brain is often described as a soft organ,[24] with an elastic modulus of only about 100 Pa at 1 Hz.[25] This low stiffness is thought to facilitate synapse formation and robust electrical signaling during tissue development.[26,27] Neuronal membranes are likewise built from ductile lipid bilayers, whose softness allows embedded ion-channel proteins to undergo conformational changes that open or close their pores in response to stimuli such as voltage or neurotransmitters.[28] It also permits ion channels to diffuse, reorganize, and be inserted or removed over time, thereby contributing to synaptic plasticity.[29] At larger scales, neurons can physically remodel during learning, a process that depends on the mechanical compliance of cellular membranes and scaffolds to reshape existing connections and form new ones for long-term memory storage in neural networks.[30]

The softness of neuronal membranes plays a central part in the energetics and adaptability of neural signaling. Ion channels embedded in lipid bilayers operate between aqueous electrolytes on either side, enabling rapid ion transport through water while minimizing the energetic cost of gating. Individual channels undergo conformational transitions on energy scales comparable to k_BT, yet can regulate fluxes exceeding 10^8 ions per second.[31,32] Synaptic switching therefore consumes only femtojoules per event, giving biological neural systems an energy efficiency far beyond that of conventional electronic circuits.[33] By enabling both efficient biophysical signaling and structural plasticity, the mechanical softness of neural substrates contributes to the extraordinary computational capabilities of the brain.

Soft fluidics employs deformable, biomolecular, or entirely fluidic systems to achieve memristive behavior inspired by biology implementing intrinsically soft and wet structures of lipid membranes, ion channels, hydrogels, polymer networks, *etc.* In soft ionic memristors, the device components can move or reconfigure significantly during operation. They also bring biocompatibility and an ability to host biological entities directly. The interplay between mechanical compliance and ionic transport is a recurring theme, as soft systems can deform in response to ion flows. This deformation can in turn influence conduction, creating a memristive loop. In this section, we explore two major categories, those utilizing biological systems and ionic polymers (Table 1).

2.1 Biological membrane and protein nanopores

Biological membranes, composed of lipid bilayers with embedded proteins (Fig. 3a and b), have evolved to perform ionic information processing. Central to this function are ion channels, whose conductance is regulated by voltage, ligand binding and other external stimuli.[34] The Hodgkin–Huxley framework can itself be viewed as memristive, in that channel gating variables evolve according to voltage history and thereby produce history-dependent conductance that is essential for action-potential generation.[35] Although biological nanopores have been studied extensively as sensors for the detection of small molecules,[36–40] this same principle has also motivated the direct use of biological ion channels as building blocks for artificial synapses.

An instructive example of a bioengineered ion-channel memristor is the hydrophobically gated nanopore based on fragaceatoxin C (FraC), a pore-forming toxin.[41] Here, a hydrophobic constriction undergoes voltage-driven electrowetting transitions between wet conductive and dry vapor-blocked states, generating strongly history-dependent conductance with large on/off ratios (Fig. 3c). When a small number of mutant FraC pores are reconstituted in a lipid bilayer, the device displays analogue switching, stochastic state transitions and synapse-like plasticity under pulsed stimulation. This system illustrates how protein nanopores can serve as genetically encodable, structurally precise building blocks for iontronic memristors (Fig. 3d).

A mechanistically distinct route to protein-based neuromorphic elements is offered by beta-barrel nanopores widely studied for sequencing applications,[42,43] in which lumen charge governs both open-pore rectification and voltage-driven mechanical gating (Fig. 3e). A recent mutation-theory-simulation study of aerolysin showed that localized charges in the pore lumen drive ionic accumulation and depletion that set the polarity and magnitude of rectification, whereas gating emerges on slower timescales when strong electric fields dissociate counterions from lumen charges and promote local beta-barrel deformations, yielding a bistable open/closed response and memristive hysteresis. By tuning the spatial distribution of lumen charge with site-specific mutations, the authors engineered an aerolysin mutant with enhanced

Table 1 Representative soft nanofluidic systems exhibiting memristive ionic dynamics

System class	Ref.	Material/fluidic system	Size	Mechanism	Stimulus class	Switching speed	Retention time	Energy consumption
Bio-nanopore	41	β-barrel nanopore (FraC mutants) in KCl	nanopore with hydrophobic segment of ∼1.2 nm	Hydrophobic gating yielding bistable wet/dry states (vapour bubble)	Triangular voltage sweeps (150 mV, 2 s)	∼2 Hz	Seconds to tens of seconds	∼pJ per synaptic event
Bio-nanopore	44	β-barrel nanopores (aerolysin and MspA mutants)	nanopore with nanometre-scale lumen constriction	Field-driven counter-ion dissociation and local deformation	Pulse trains (110 mV, 5–10 ms)	100–200 Hz	Volatile (state depends on lipid reconfiguration)	N/A
DIB	48	Droplet interface bilayer between 100 mM KCl droplets	600 nL per droplet	Voltage-driven electrocompression/electrowetting changing bilayer area/thickness	Pulse trains (0/200 mV, 0.1 s)	∼2 Hz	Seconds to tens of seconds	4–8 pJ per spike
DIB	49	Droplet interface bilayer between 500 mM KCl droplets	300 nL per droplet	Voltage-driven restructuring of lipid bilayer (area/thickness and headgroup dielectric loss)	Sinusoidal voltage (10–100 mHz; 80–150 mV)	N/A	Volatile (state depends on lipid reconfiguration)	N/A
DIB	50	Droplet interface bilayer between 500 mM KCl droplets	200 nL per droplet	Voltage-driven restructuring of lipid bilayer (area/thickness and headgroup dielectric loss)	Pulse trains (150 mV, 1–2 ms)	∼100 Hz	∼tens of seconds	N/A
DIB	51	Alamethicin-doped droplet interface bilayer between 500 mM KCl droplets	200 nL per droplet	Channel density/permeability changes *via* voltage-driven insertion of alamethicin in ion channels	Pulse trains (130 mV, 10–1500 ms)	20–50 Hz	∼2 s	pW–nW
DIB	53	Droplet interface bilayer formed by printed networks of aqueous droplets	∼500 pL droplets	Platform work	Thermal stimulus for printing (55–60 °C) and mechanical compression tests (mHz–Hz)	N/A	N/A	N/A
Brain organoid	59	Human neural organoids interfaced with microelectrode array	N/A	Stimulation-modified neural network activity/connectivity in human neural organoids	Electrical theta-burst stimulation delivered 4× with 13-min interval	Short-term effects milliseconds after stimulation	Longer-term plasticity assessed from 60–180 min post stimulation and additional assays over hours	N/A
Brain organoid	62	*In vitro* cortical neuron cultures on multi-electrode array	mm-scale culture on chip	Cultured cortical networks adapting synaptic connectivity and firing patterns	Closed-loop electrical stimulation	Apparent learning/adaptation reported within ∼5 minutes in closed-loop task	N/A	N/A
Ionic polymer	72	Organic electrochemical RAM: p(g2T-TT) channel with ion-gel electrolyte	Channel ∼45 µm × 15 µm	Electrochemical doping/de-doping	Pulse trains (1 V, 1 µs)	∼0.05 GHz	∼minutes	∼80 fJ per write
Ionic polymer	76	All-inorganic ionic polymer memristor: Au/APP/ITO on PET	APP layer thickness ∼250 nm	Voltage-driven migration/accumulation of mobile ions in ammonium polyphosphate	Pulse trains (0.1–0.4 V, 20 ns–20 µs)	∼0.05 GHz	∼10 000 s retention	∼nJ per write
Ionic polymer	77	Proton-enabled peptide memory: Y7C peptide film coupled to IGZO synaptic transistor	Y7C film thickness ∼117 nm, ∼200 × 200 μm^2	Ag redox and filament formation driven by humidity-activated proton transport in tyrosine-rich peptide films	Humidity + pulse trains (1 V, 0.1–1 s)	10 000–0.1 Hz	Seconds to hundreds of seconds	N/A

synaptic plasticity and demonstrated potentiation and depression by voltage pulse sequences, providing a rational design framework for programmable ionic synapses (Fig. 3f).[44]

The advantage of genuine cell membranes, or their synthetic analogues, is that they naturally embody many of the features required for computation, including nonlinearity, time

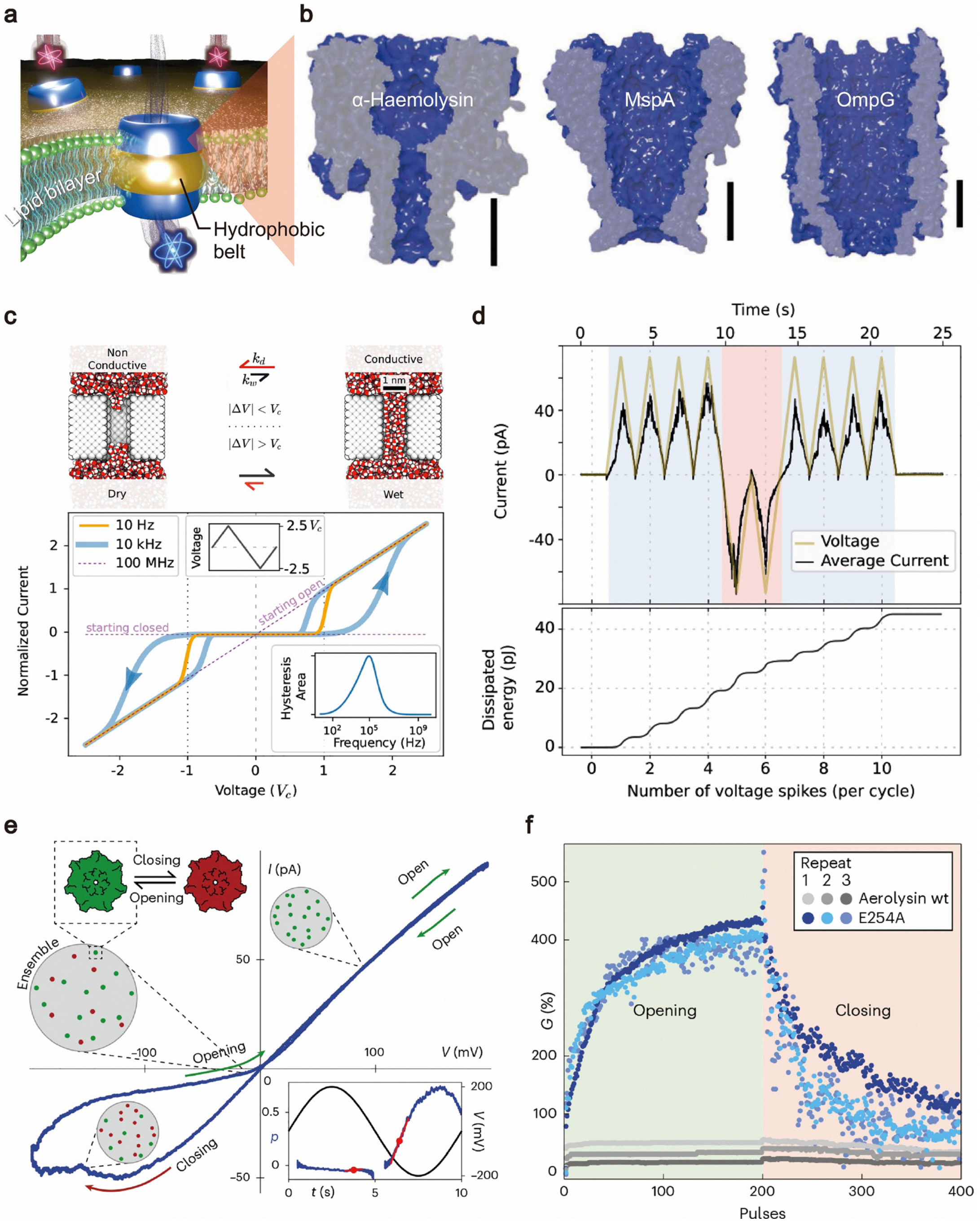

Fig. 3 Memristive gating in biological nanopores. (a) A sketch depicting a simplified model of protein channels inserted in a lipid bilayer. (b) Structures of α-haemolysin, MspA, and OmpG. Adapted with permission from ref. 42. Copyright 2016 Springer Nature. (c) Electrowetting mechanism and normalized current–voltage loops showing frequency-dependent hysteresis. (d) Spike-train operation yielding synapse-like current responses and cumulative energy dissipation. Adapted with permission from ref. 41. Copyright 2023 Creative Commons CC BY. (e) Ensemble opening/closing produces a pinched hysteresis loop in the *I*–*V* characteristics. (f) Plasticity under repeated voltage pulses for wild-type and charge-mutant aerolysin, illustrating potentiation and depression of conductance. Adapted with permission from ref. 44. Copyright 2025 Creative Commons CC BY.

dependence and plasticity. For example, incorporating *N*-methyl-D-aspartate (NMDA) receptors into a lipid bilayer could in principle reproduce aspects of Hebbian plasticity.[45] Although such systems remain bioengineered and experimentally complex, they illustrate how soft memristors can be directly biomimetic and function in ways that closely resemble natural synapses.

2.2 Droplet interface bilayers

Droplet interface bilayers (DIBs) extend the bionanopore concept from a single molecular channel to a mesoscopic, reconfigurable synaptic unit.[12] In these systems, two electrolyte droplets are brought into contact within oil, where opposing lipid monolayers zip together to form a bilayer patch that is electrically addressable in much the same way as a cell membrane (Fig. 3a).[46,47] Despite this simple geometry, DIBs can already support a surprisingly rich repertoire of synaptic functions even in the absence of ion channels, including facilitation and depression reminiscent of spike-rate-dependent plasticity, Hebbian learning, and even associative learning in a Pavlovian protocol under voltage-pulse stimulation.[48]

The origin of memory in DIBs is mechanistically distinct from protein-pore gating. Here, a voltage sweep couples ionic relaxation to interfacial mechanics (Fig. 4a): residual charge, field-driven ion adsorption within the headgroup region, and the slow recovery of membrane order together bias the conductance reached on the next cycle.[49] Bilayer capacitance is likewise not a passive quantity, but evolves with voltage history as membrane tension, area and dipole orientation shift. The resulting element therefore behaves as a coupled memristor–memcapacitor rather than as a purely resistive switching device (Fig. 4b).[50]

This coupling is what makes DIBs a particularly powerful extension of biological nanopore concepts for neuromorphic devices. Whereas the systems in Section 2.1 derive their dynamics primarily from the conformational landscape of a specific protein channel, DIB synapses expose several tunable state variables, including electrolyte composition, droplet size,

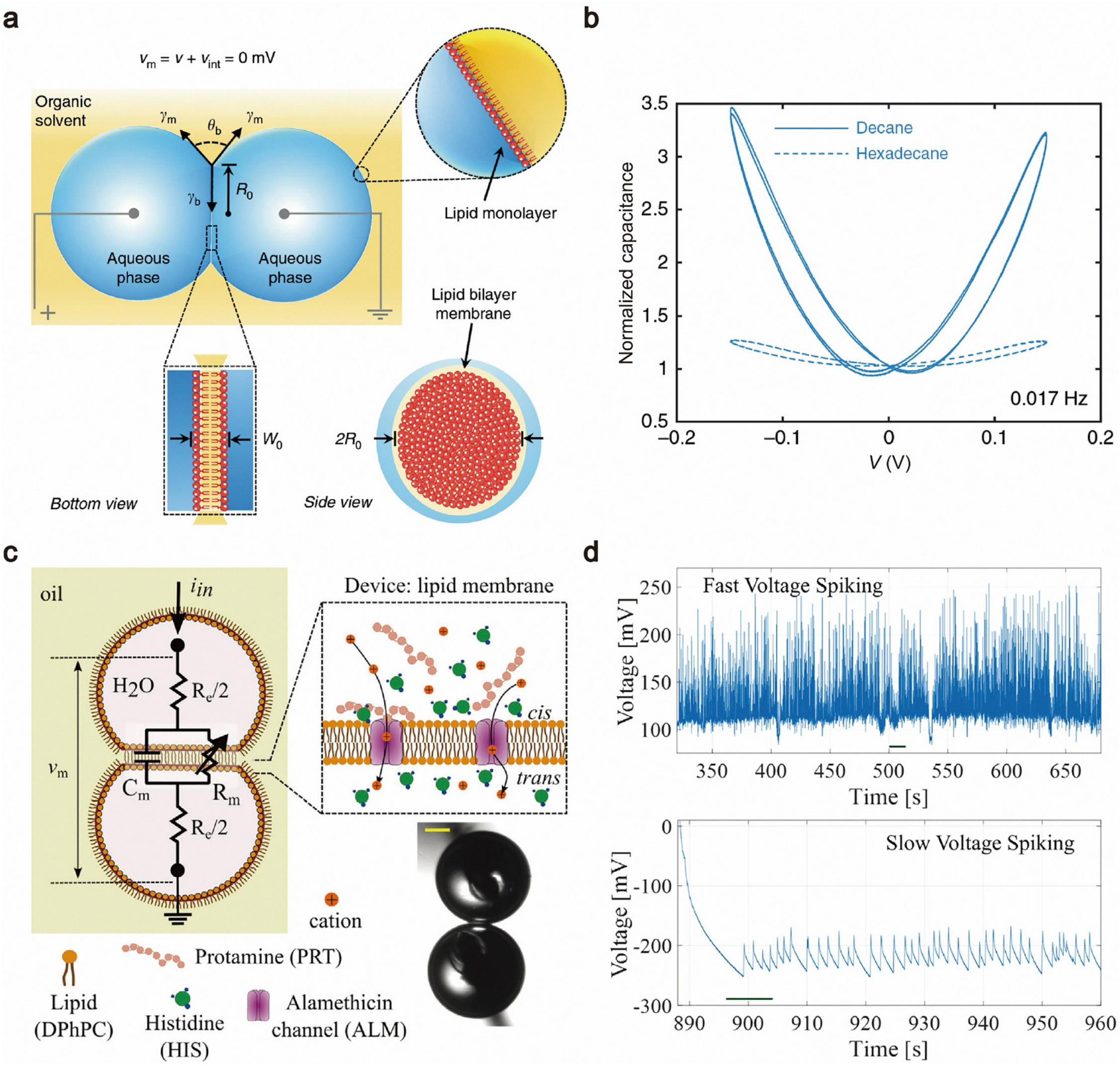

Fig. 4 Droplet-interface bilayers as voltage-responsive memcapacitors and spiking membrane neurons. (a) Droplet-interface bilayer (DIB) platform in which two aqueous droplets in oil self-assemble a lipid bilayer that can host transmembrane channels; schematic (top) and optical micrograph (bottom). (b) Voltage-driven electrowetting and electrocompression reshape the bilayer geometry, modulating membrane thickness and radius as coupled state variables. The resulting nonlinear pinched capacitance–voltage hysteresis depends on the oil phase, demonstrating memcapacitance. Adapted with permission from ref. 50. Copyright 2019 Creative Commons CC BY. (c) Equivalent circuit for DIB devices with electrolyte resistance in series with a membrane branch comprising a state-dependent membrane resistance in parallel with membrane capacitance; inset, reconfigurable channel networks and mobile charged modulators coupling ionic transport to membrane state. (d) Under dc current bias, these internal dynamics can generate neural-like voltage spiking with distinct fast and slow regimes, consistent with a feedback cycle of channel insertion/opening and polyelectrolyte-mediated blocking and charge redistribution across *cis*/*trans* reservoirs. Adapted with permission from ref. 51. Copyright 2024 John Wiley and Sons.

bilayer lipid chemistry and mechanical boundary conditions. The learning rule can therefore be engineered at the level of interfacial physics. Protein nanopores can nonetheless be incorporated as modular components (Fig. 4c and d).[51–54] Introducing channels such as alamethicin,[52] mechanosensitive channel of large conductance (MscL),[53] or engineered mutants[54] adds a second layer of memory through channel population dynamics, effectively combining molecular and interfacial plasticity within a single soft element.

Equally important, droplets offer a route to scalability that single-bilayer protein devices struggle to match. Droplets can be generated, positioned, and connected in parallel by microfluidics, patterned into networks, or assembled as emulsions into dense soft circuits, turning the bilayer into a repeatable unit cell for wet neural architectures.[55] The remaining hurdles are practical-bilayer fragility and device-to-device variability, motivating polymer-stabilized membranes, partial gelation and chip-based confinement as strategies to make large droplet arrays both reproducible and long-lived.

2.3 Living neural networks and organoid intelligence

Brain organoids, three-dimensional neural tissue constructs grown from stem cells, are emerging as soft, living substrates for neuromorphic computing.[56,57] These mini-brains are physically soft with stiffness on the order of only a few hundred Pascals.[58] This extreme mechanical softness means organoids are predominantly fluidic systems, composed of cells and extracellular matrices akin to soft membranes, which enables efficient ion transport through the aqueous extracellular space and across flexible cell membranes, much like ionic polymers in artificial devices.

Memristive behavior is intrinsically realized in organoid neural networks *via* synaptic plasticity. In these living networks, each synapse acts like a nanoscale memristor whose strength or conductivity adjusts based on prior activity. Biological synapses achieve this through ionic and molecular mechanisms. For instance, repeated stimulation causes residual Ca^{2+} buildup and receptor modifications that temporarily or permanently change synaptic efficacy. Experiments have confirmed that brain organoids exhibit both short-term and long-term synaptic potentiation and depression in response to stimulation (Fig. 5a–c).[59] In other words, organoids can undergo short-term memory with milliseconds-to-seconds facilitation/depression of a synapse as well as long-term memory allowing persistent strengthening or weakening analogous to learning. Although these plastic changes mirror the memristive behavior engineered in ion-based artificial synapses, they emerge naturally from the underlying biochemistry of the organoids. Notably, recent high-profile work demonstrated that human neural organoids constitute the fundamental building blocks of learning. They form functional synapses with glutamatergic/GABAergic receptors and show activity-dependent gene induction accompanying synaptic potentiation.[59] Such findings demonstrate that a soft living organoid can perform analog memory storage through ionic synaptic modifications, effectively functioning as a memristive network without any solid-state components.

The link to artificial nanofluidic memristors becomes clearer when these biological processes are expressed in physicochemical terms. Residual Ca^{2+} accumulation in synapses resembles the delayed ionic relaxation that sustains electric-double-layer memory, while neurotransmitter binding and release parallel reversible adsorption and desorption processes at functionalized interfaces. These correspondences do not imply strict equivalence, but they do provide a useful design language for translating organoid-like plasticity into engineered iontronic devices.

By virtue of their intrinsic ionic conduction and synaptic plasticity, brain organoids are emerging as experimental platforms for neuromorphic task execution. Their distributed neuronal circuits support collective information processing reminiscent of biological brains. For example, organoids can generate organized electrical oscillations and synchronized firing patterns analogous to brain waves.[59] Notably, spontaneous network oscillations in a human cortical organoid have been shown to recapitulate electroencephalography (EEG) rhythms observed in the preterm infant brain, suggesting the emergence of functional connectivity and critical dynamics favorable for computation. More directly, organoids have been harnessed for computational tasks through learning-based frameworks. In a landmark study, a living brain organoid was incorporated into a reservoir-computing architecture, in which a three-dimensional neural organoid was coupled to a high-density microelectrode array for stimulus encoding and signal readout.[60] The organoid exhibited rich nonlinear dynamics together with a fading memory of past inputs, enabling time-dependent computation. Remarkably, the system achieved unsupervised learning through network reorganization, allowing it to perform speech recognition and even predict chaotic mathematical equations in real time.[60] In this setting, the soft organoid functioned as a reconfigurable analogue processor whose internal synaptic weights adjusted autonomously in response to training stimuli.

Neuromorphic behavior in biological networks has also been illustrated by demonstrations of goal-directed learning in cultured neuronal assemblies, a line of work often grouped under the emerging concept of organoid intelligence. In 2022, a cultured layer of ∼800 000 human cortical cells interfaced with electrodes, frequently described as a two-dimensional organoid or cortical network, was shown to learn to play Pong through feedback-driven training (Fig. 5d and e).[61,62] Over time, the neuronal culture progressively reshaped its firing dynamics in response to the game environment, revealing a rudimentary form of skill acquisition and memory that sustained paddle control. The DishBrain experiment illustrates that living neural networks can acquire adaptive behavior and store memory in a manner analogous to a learning machine. Taken together with three-dimensional organoid studies, these findings offer proof-of-concept that biological soft systems can realize computational functions such as pattern recognition, control, and prediction by leveraging synaptic plasticity.[59] During learning, the iontronic circuits of these networks are continuously reshaped by the malleable, fluidic tissue itself, exemplifying

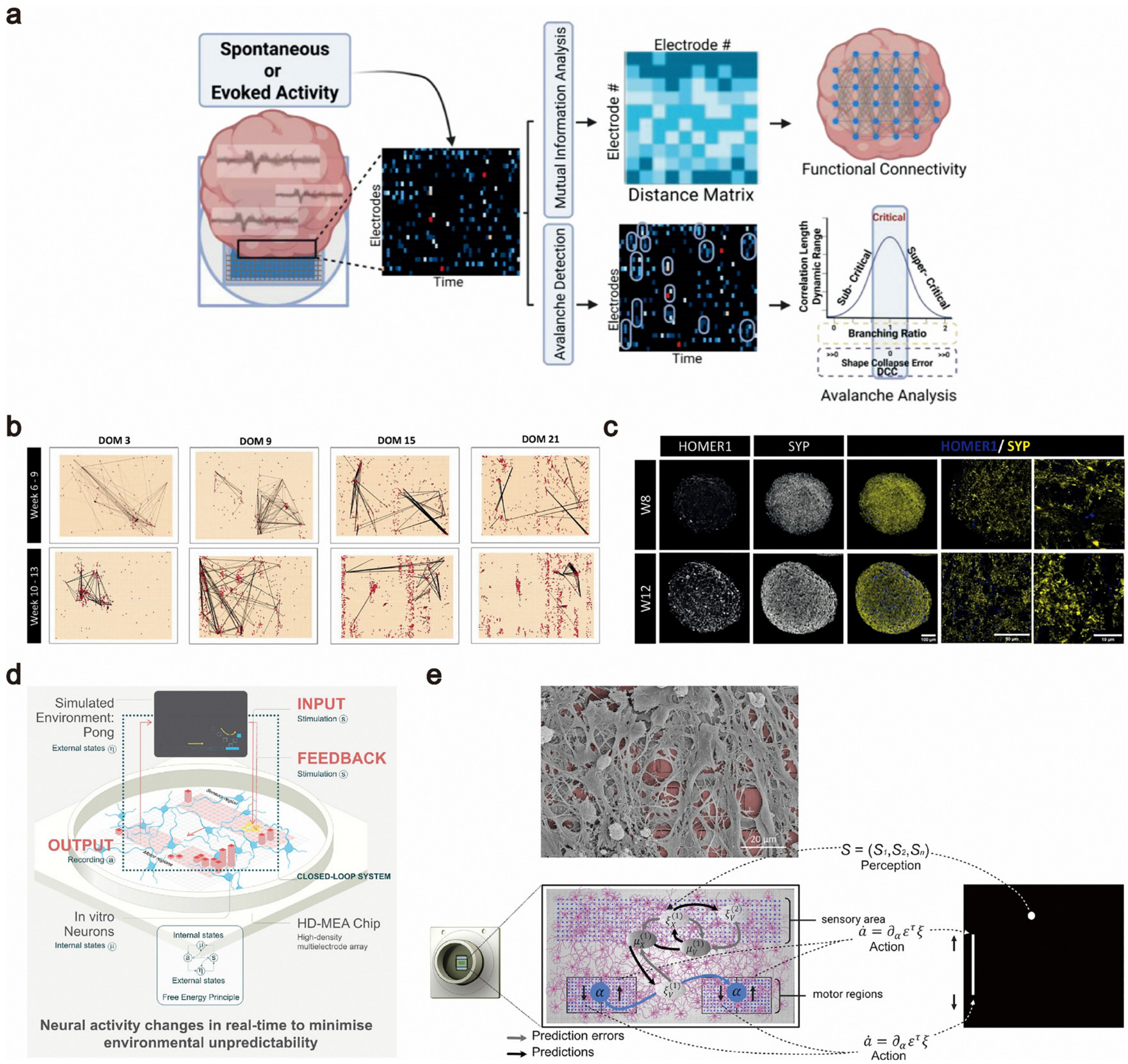

Fig. 5 Living neural networks as soft ionic substrates for computation. (a) High-density microelectrode array interfacing enables simultaneous recording and stimulation of cortical organoids; analysis workflows extract functional connectivity and neuronal criticality from spontaneous and evoked activity. (b) Example functional-connectivity graphs reconstructed across development, illustrating evolving edge weights and active nodes across the electrode field. (c) Immunostaining of pre- and postsynaptic markers in cortical organoids indicates progressive synaptogenesis that underpins emergent network dynamics. Adapted with permission from ref. 59. Copyright 2025 Springer Nature. (d) Closed-loop DishBrain embodiment, in which cultured neurons on a microelectrode array receive sensory stimulation encoding the Pong game state and feedback to drive goal-directed adaptation. (e) Mapping of sensory and motor channels on the array and a conceptual active-inference loop linking neuronal activity to actions and prediction errors in the virtual environment. Adapted with permission from ref. 62. Copyright 2022 Creative Commons CC BY.

how mechanical softness and neuromorphic function are intrinsically coupled in organoid computing.

Organoids derive their computing capability from a unique combination of material softness and biological architecture, standing in sharp contrast to traditional electronic hardware. They consist of living neurons, supporting glial cells and the extracellular matrix they secrete.[59] Within an aqueous milieu, neurons self-organize into dense three-dimensional networks interconnected by thousands of synapses. Soft phospholipid bilayer membranes act as the basic ionic capacitive and resistive elements. Owing to their nanometer-scale thickness and mechanical softness, these membranes readily undergo conformational changes in response to ion binding or voltage fluctuations, enabling electrically responsive soft-matter behavior. Protein ion channels and receptors embedded within the membranes respond to mechanical and electrical cues by opening or closing, thus dynamically regulating ion transport. This tunability enables ion transport to display rich nonlinear responses, such as channel inactivation and neurotransmitter depletion, that are essential for computation. Additionally, the nanoscale synaptic cleft forms a soft ionic domain that transiently concentrates neurotransmitters and ions during activity, producing short-lived chemical gradients. Repeated signaling transiently reshapes the chemistry of the synaptic cleft, analogous to the state evolution of an active region, enabling synaptic strength to encode a short-term memory of recent activity.[63] At its core, the computational substrate of organoids is a network of soft, ion-conducting components from lipid bilayers and protein ion channels to neurotransmitters. Mechanical softness and flexibility are central to function at every level, with soft membranes and cytoskeletal elements enabling synaptic reorganization during learning, from the creation of new connections to synaptic growth during potentiation. This stands in contrast to rigid silicon chips, where circuit elements are fixed. In organoids, the wiring is fluid. Indeed, studies have observed organoid neurons forming new circuits and strengthening connectivity in response to stimulation, effectively rewiring their microcircuitry as learning progresses. Such plastic reconfiguration is enabled by both the biochemical machinery and the compliant physical matrix in which neurons reside.

The advent of brain organoids as computing units carries profound implications for bio-inspired and neuromorphic computing. First, these living systems offer a level of adaptive parallelism and energy efficiency.[64] Their soft iontronics approach to computation could overcome limitations of traditional rigid electronics by operating in an analog, event-driven fashion with minimal chemical energy. Intrinsic mechanical softness permits conformal biointerface integration, enabling flexible three-dimensional electrode meshes to envelop organoids without damage and opening the door to wetware coprocessors that physically integrate with sensing or robotic systems. Moreover, organoid computing systems naturally embody features that hardware engineers struggle to reproduce, such as self-organization and fault-tolerance. Through memristive synapses, these systems achieve on-chip learning and memory without explicit programming, and even when partially damaged, the remaining tissue can reorganize to restore function, echoing recovery mechanisms in the brain. This mortal yet regenerative substrate thus defines a new computational paradigm, in which hardware itself can grow, adapt, decay, and be renewed. Despite their promise, organoids pose major challenges for reliable computing, including biological variability, finite lifespans, and ethical issues inherent to human-derived neural systems. Nonetheless, recent studies have validated the core concept that soft living neural networks can perform meaningful computations. As research progresses, it is conceivable that hybrid approaches integrating organoid-based processors with conventional electronic systems could be explored, potentially harnessing the complementary strengths of biological adaptability and electronic precision.

2.4 Ionic polymers and soft iontronics

Rather than borrowing the molecular machinery of biology, ionic polymers offer a synthetic, processable medium in which memory is written into ion distributions and soft-matter relaxation, enabling devices that are flexible, scalable, and compatible with large-area manufacturing.[65–68] They span electrolyte-swollen hydrogels, ionomers such as Nafion, and polyelectrolyte networks built from biopolymers. Their defining feature is that the conductor is not a fixed pore but a dynamic matrix of charged segments binding and releasing counterions, polymer domains swelling or densifying, and nanoscale morphology evolving under bias (Fig. 6a and b). These slow internal degrees of freedom provide the state variable for memristive behavior, while the macroscopic form can be cast as films, patterned over centimeters and integrated on soft substrates.[69,70]

The mechanism contrasts with the biological motifs. In protein nanopores, memory is encoded in conformational landscapes of a channel. In droplet bilayers, it emerges from coupled ionic relaxation and interfacial mechanics. In organoids, it is distributed across synapses and gene programs. Polymer synapses, by comparison, store their state in the physics of ion binding, diffusion, and viscoelasticity within a single material layer, trading biological richness for device-level simplicity and manufacturability.[71]

A common architecture is the ionic gel, in which an electrolyte is immobilized within a polymer scaffold. Because ions move through a crowded network rather than a free solution, relaxation is slowed and conductance lags the applied field.[72] Fixed charges add a further source of history dependence by transiently trapping counterions and altering local osmotic pressure, while the same redistribution of ions can couple to electromechanical strain so that swelling and conductivity evolve together. The resulting behavior appears as electrical hysteresis, often in the form of a pinched current–voltage loop and, in some materials, a persistent deformation that in turn feeds back on transport (Fig. 6c).[72]

Natural polyelectrolytes provide a clear example of how chemistry and mechanics can become memory.[73] In alginate gels, crosslinking is mediated by divalent cations such as Ca^{2+}, so an applied field can drive ion exchange and create spatially heterogeneous crosslink densities (Fig. 6d–f). Because both the ionic profile and the polymer network relax only slowly, regions with distinct mechanical and ionic properties can persist after stimulation, leaving a structural memory that is later read out through changes in ionic conductance. More generally, polysaccharide gels with path-dependent hydration or ionic crosslinking offer a route to purely ionic memory without invoking metallic filaments or electronic charge storage.

Denser ionomers provide a complementary pathway in a solid membrane. In Nafion, protons drift through nanometer-scale ionic domains lined with sulfonate groups, and a fraction becomes transiently trapped or stabilized by local hydrogen-bond networks.[74,75] Slow rearrangement of these ionic clusters makes resistance evolve with voltage history, yielding memristive transport at low bias. Bipolar ion-exchange membranes extend this concept by adding interfacial reaction dynamics: forward bias promotes water dissociation at the junction, whereas recombination proceeds with different kinetics, so the interfacial ionic state carries memory.[74,75]

A major application space in which ionic polymers excel is flexible and wearable electronics. Using gels and polymer electrolytes, researchers have developed iontronic capacitive touch sensors and synaptic transistors for human–machine interfaces, naturally extending to flexible memristive artificial synapses. For example, Zhao *et al.*[76] reported a flexible all-inorganic ionic polymer-based memristor that exhibited stable synaptic behavior. Although the detailed operating mechanism

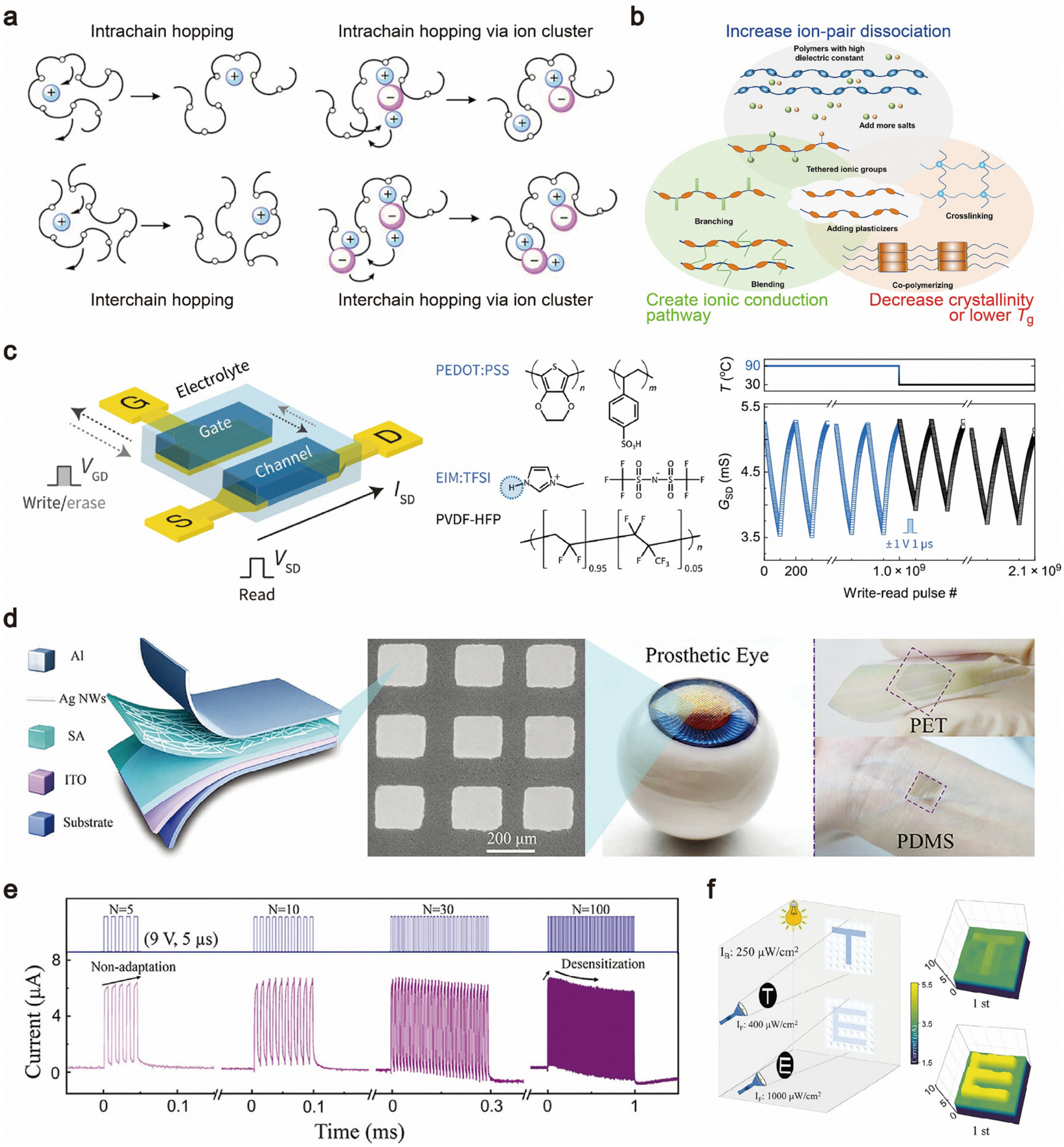

Fig. 6 Soft polymer iontronics as a bridge from transport physics to adaptive sensing. (a) Schematic view of ion motion in polymer electrolytes, highlighting intra-chain and inter-chain hopping that set the intrinsic relaxation times governing ionic conductivity. (b) Materials-level design levers for raising conductivity. Adapted with permission from ref. 66. Copyright 2023 Creative Commons CC BY. (c) Solid-state organic electrochemical random-access memory in which an ion-gel gate modulates the doping state of a conjugated-polymer channel, enabling low-voltage analog weight updates and temperature-resilient operation with sub-microsecond programming and $>10^9$ write-read endurance. Adapted with permission from ref. 72. Copyright 2020 The American Association for the Advancement of Science. (d) Flexible sodium-alginate complementary memristor architecture and array-level integration, illustrating conformable form factors for prosthetic and wearable platforms. (e) Pulse-train responses in the alginate device that transition from non-adaptation to desensitization as stimulus number increases, implementing a hardware analogue of sensory gain control. (f) A neuromorphic vision concept in which adaptive preprocessing improves pattern recognition across changing background intensity, linking ionic memory directly to perception-level tasks. Adapted with permission from ref. 73. Copyright 2024 John Wiley and Sons.

of this device lies beyond the scope of this discussion, it likely relies on ionically driven internal reconfiguration within an inorganic polymeric matrix to achieve low-voltage, non-volatile resistance modulation. More broadly, such results demonstrate how ionic conduction coupled to slow structural or chemical rearrangements in polymeric systems can support memory effects suitable for neuromorphic functionality.

Ionic polymers also allow computation to be coupled to the environment. Humidity-responsive peptide films, for example, gate proton conduction through water uptake, so resistance depends on both electrical history and ambient chemistry.[77,78] This multifunctionality suggests polymer synapses that sense and learn within the same material, an ability that is difficult to achieve with isolated protein pores or fragile bilayer droplets.

In practice, polymer iontronics is defined by a useful compromise. These devices typically operate at low voltage and can retain memory for minutes to hours because ionic and structural relaxation is slow, although switching speeds are often limited by diffusion and viscoelasticity. Their decisive advantage is integration by processing rather than by assembly, in terms of the fact that films can be cast, coated, or printed into dense arrays, positioning ionic polymers as a pragmatic counterpart to the biological systems.

3. Solid-state nanofluidic platforms

Having established the role of softness, we next turn to solid-state nanofluidic platforms. Unlike biological synapses or ionic polymer systems, solid-state nanopores and nanochannels are mechanically rigid. Their defining feature is not ductility or deformability, but geometric and chemical stability during operation. At first glance, this rigidity may seem disadvantageous compared with the adaptive softness of neurons or ionic polymers. Yet solid-state nanofluidic systems compensate for the absence of mechanical compliance by exploiting field-driven ionic reconfiguration, electrochemical memory, and interfacial phenomena under confinement. Advances in nanofabrication now allow pores to be engineered at dimensions approaching those of biological ion channels, opening transport regimes shaped by ion dehydration, Coulomb blockade and, in some cases, even quantum effects.[79–82] More importantly, rigidity brings precise fabrication, reproducibility and compatibility with large-scale integration,[83,84] making solid-state nanofluidics the most realistic route towards mass-produced ionic neuromorphic hardware. Whereas neurons rely on mechanical softness to realize plasticity, solid-state nanofluidic memristors instead harness the electrochemical softness of ionic states. In both cases, memory arises from the delayed relaxation of internal degrees of freedom. In neurons, these include protein conformations and biochemical cascades; in rigid nanopores, they are primarily ionic distributions, hydration states and interfacial configurations. Solid-state nanofluidic memristors can therefore be viewed as rigid scaffolds for wet intelligence: architectures in which ions compute, remember and adapt within mechanically stable confinement (Table 2).

3.1 Counterion dynamics in micro- and nanochannels

A central source of memristive behavior in rigid nanochannels is the electric double layer. When a voltage is applied across a permselective nanochannel or nanopore, ions begin to redistribute, creating regions of enriched or depleted ionic concentration (Fig. 7a).[85,86] If the voltage is changed before complete equilibration, residual ionic gradients and space-charge distributions from the prior state can persist and modulate subsequent transport, endowing the channel with a memory of its bias history (Fig. 7b). Indeed, this mechanism underlies some of the earliest demonstrations of memristive behavior in ionic systems, where slow counterion dynamics in nanopore electric double layers give rise to hysteretic current–voltage responses.[87] In its simplest form, a fixed-charge conical nanopore rectifies ionic current, and when the bias is swept faster than ionic relaxation, residual depletion and accumulation persist at opposite ends of the pore, producing the pinched *I–V* hysteresis with inherently frequency dependence, wherein slow voltage sweeps allow ions to equilibrate and eliminate memory, intermediate sweep rates produce strong hysteresis, and extremely fast sweeps yield an almost ohmic response as ionic motion becomes effectively frozen,[88,89] reflecting the fundamental timescales of ion migration and capacitive charging in nanoscale channels.

The same mechanism extends beyond nanometer confinement. Single channels with asymmetric geometry, surface charge or salinity can exhibit ionic rectification[90,91] and, in some cases, negative differential resistance,[92,93] because the applied field establishes longitudinal depletion and accumulation regions. Strikingly, memristive behavior persists even for micrometer-wide channels, where history dependence can be traced to incomplete depletion and delayed re-equilibration of ions within extended space-charge layers upon field reversal.[94]

The underlying ion dynamics is set by a diffusion-controlled timescale that can be engineered through geometry. Starting from the coupled Poisson–Nernst–Planck–Stokes equations, the relaxation time is predicted to scale as $\tau \approx L^2/(12D)$ for a channel of length L and ionic diffusivity D (Fig. 7c).[95] The quadratic dependence on L provides a simple design handle: doubling the channel length increases τ by roughly a factor of four, prolonging the lifetime of ionic memory. Channel taper and wall charge further reshape the concentration polarization field[96–100] and tune the prefactor, offering additional control (Fig. 7d). Analytical reductions and finite-element calculations consistently support this diffusive scaling and its sensitivity to geometric and interfacial parameters.[95]

This geometric programmability allows to adjust the temporal structure for a target computation. In colloid-filled tapered microchannels that embed a conducting nanochannel network, transient salt concentration polarization yields stable volatile memristors whose retention time can be selected by channel length.[101] Exploiting this tunability, individual channels have been used as synaptic elements for reservoir computing, where their nonlinear, history-dependent conductance transforms temporal voltage pulse trains into separable states. In a benchmarking task, time-series encodings of handwritten digits were classified with a simple readout layer, achieving performance comparable to solid-state dynamic memristor reservoirs.[101]

Together, even structurally rigid channels can display memristive ion transport because counterions and co-ions relax on finite timescales after the electric field is changed. In these purely electrostatic devices, memory is encoded in the slow build-up and decay of space charge, producing pinched current. Such systems have provided a clean starting point for ionic memory and have already been assembled into simple networks that execute logic and computing functions. The next step is to move beyond volatile, single-mechanism behavior towards non-volatile switching and multilevel states, while

Table 2 Hard nanofluidic systems with memristive ionic dynamics

System class	Ref.	Material/fluidic system	Size	Mechanism	Stimulus class	Switching speed	Retention time	Energy consumption
Counterion dynamics	88	Track-etched PET double conical nanopores, KCl concentration gradients	Tip diameter $\sim$5–20 nm	Broken symmetry from divalent-ion screening and pH-driven deprotonation	Pulse trains (10 V, 1.0–1.5 s)	$\sim$1 Hz	$\sim$20 min	N/A
Counterion dynamics	89	Conical polyimide nanopores, 0.1 M KCl	Tip diameter $\sim$20–50 nm	Voltage-derived transient ion concentration polarization	Pulse trains (2 V, 2–1000 ms)	1–50 Hz	$\sim$40 s	N/A
Counterion dynamics	101	Tapered micro-fluidic channel, 10 mM KCl	Channel tip 5 μm, base 200 μm, length 150 μm	Voltage-derived transient ion concentration polarization	Pulse trains (2.5–5 V, 0.75 s)	$\sim$1 Hz	$\sim$1 s	$\sim$1–10 μJ
Space confinement	104	Angstrom-scale slit nanochannels (theory)	Slit height $\sim$0.7–1.4 nm	Electric-field-induced ion clustering in Å-scale slits	AC voltage (0.1 V, 100 Hz)	$\sim$100 Hz	N/A	N/A
Space confinement	105	Active carbon 2D channel, 1 mM CaCl$_2$	Channel height $\sim$5 nm	Surface adsorption/desorption-mediated ion transport	Pulse trains (1 V, 10 s)	$\sim$0.1 Hz	$\sim$hours	N/A
Space confinement	106	MoS$_2$ and hBN 2D nanochannel, KCl, CaCl$_2$, AlCl$_3$	Channel height 0.7–2 nm	Transient concentration polarization and ion–ion/surface-charge interactions	Write pulses $\sim$20–60 s	$\sim$0.1 Hz	Short ($<$100 s) and long term ($>$3 days) memory	N/A
EOF	107	Immiscible liquid–liquid interface in nanochannels	PDMS nanochannel, 200 nm × 63 nm × 10 μm	Electroosmosis-derived motion of liquid–liquid interface confined in nanochannels	Pulse trains (4–10 V, 0.5 s)	2 Hz	$>$20 min	N/A
Optical	109	Graphene–MoS$_2$ heterojunction nanopore, 1 M KCl	Heterojunction nanopore size $\sim$2–20 nm	Light-induced electron–hole separation in a p–n hetero-junction nanopore inducing photovoltage-driven ion pumping	Light pulses (365–1050 nm, 0.2–5 Hz)	Response time 50 ms	N/A	16.3 mW/cm^2 per light pulse
Optical	111	Layered graphene oxide nanochannel	Lamellar graphene oxide nanochannel, spacing $\sim$0.42 nm; length mm-scale	Light illumination-driven Na$^+$ migration/ion redistribution in nanochannels	Light pulses (532 nm, 6 mW, 0.2 s)	5 Hz	N/A	$\sim$1.2 mJ per light pulse
Optical	112	B$_3$N subnanometer pores, mixed electrolyte (1.0 M KCl + 0.1 M NaCl) (MD simulation)	Subnanometer pores; 16 pores in $\sim$7 nm × 7 nm membrane patch (hBN monolayer)	Light illumination-driven Na$^+$/K$^+$ migration/ion redistribution in nanochannels	Pulse trains (0.5 V, 3 ns)	$\sim$0.1 GHz	$\sim$μs	0.1–100 aJ per pulse
In-pore chemistry	119	Conical PET nanopore in PBS + KCl + CoCl$_2$	Nanopore tip size 2–7 nm	Voltage-driven nanoprecipitation/dissolution inside a conical nanopore modulating aperture/selectivity	Pulse trains (2 V, 15 s)	Seconds-scale switching	N/A	N/A
In-pore chemistry	120	SiN$_x$ nanopore interfacing MnCl$_2$ and PBS	Nanopore size 100–300 nm	Voltage-driven nanoprecipitation/dissolution inside a nanopore modulating pore size	Pulse trains (0.2–0.8 V, 50 ms)	$\sim$20 Hz	$>$100 s	$\sim$0.1 nJ per pulse
EOF	23	SiN$_x$ nanopore membrane decorated with Pd and covered by graphite, 1 M KCl	Nanopore size 100 nm	Voltage-driven mechano-ionic blistering changing atomically thin pore/nanocavity geometry	Pulse trains (1.2 V, 2 s)	$>$10 Hz	N/A	N/A

retaining manufacturable, parallel integration. Counterion dynamics in hard nanochannels, therefore, remains a foundational route to nanofluidic memristors as a direct analogue of early electronic memristor concepts, but governed by mobile ions and the physics of the electric double layer.

From a design perspective, channel geometry, ion concentration and electric field strength are best treated not as independent parameters but as coupled variables. Shrinking a channel does more than shorten the transport path: it increases the surface-to-volume ratio, strengthens interfacial charging, and amplifies the effects of adsorption and depletion. Increasing electrolyte concentration, meanwhile, reduces the Debye length and can suppress hysteresis, yet under sufficiently strong driving it can also intensify concentration polarization and thereby prolong non-equilibrium ionic states. Device optimization therefore requires the co-design of geometry, electrolyte environment and electrical protocol, because retention, switching amplitude and volatility emerge from their combined action.

3.2 Ångström confinement and correlated ion states

As nanofluidic channels approach molecular dimensions down to Ångström-scale slits only a few water molecules thick, ion transport can no longer be described as a weakly perturbed continuum.[102] Strong ion–surface interactions, partial dehydration, and enhanced ion–ion correlations create metastable ionic configurations whose rearrangement can be slow. As a result, conductance can depend on stimulus timing and bias history, yielding memory effects even in mechanically rigid, crystalline channels.

A first clear route to such memory was articulated through theory and molecular simulations of monolayer electrolytes confined in sub-nanometer slits.[103,104] In this regime, an applied electric field promotes the formation of correlated ionic clusters, while reversing the field then requires these structures to dissolve and reform, producing hysteretic, history-dependent conduction in an otherwise static channel. In silico, pairing such elements could even yield neuronal-like excitability and spontaneous voltage spiking, illustrating how confinement-enhanced correlations can be promoted from molecular self-assembly to dynamical primitives for computing.[104]

Building on this conceptual framework, experiments pushed Ångström-scale confinement toward device-level programmability by exploiting the same two-dimensional slit geometry with different wall chemistries (Fig. 7e). In pristine MoS_2 channels, conductance could be potentiated by one voltage polarity and depressed by the opposite, yielding bipolar memristive updates reminiscent of bidirectional synaptic weight changes.[104,105] Activated-carbon channels, by contrast, more often showed unipolar and volatile memory, relaxing back toward a baseline after the stimulus is removed. Both the loop polarity and the memory lifetime could be tuned by confinement and electrochemistry, including channel height (sub-10 nm), salt conditions, and pH. A compact scaling argument relates the characteristic memory time to the diffusive transport time multiplied by a Dukhin-number factor that captures the strength of surface adsorption, making geometry a direct knob for programming ionic timescales (Fig. 7f).[105]

Most recently, the same platform has been shown to access the full range of nanofluidic memristor loop styles.[106] By varying electrolyte composition, pH, driving frequency, channel material and channel height, it was demonstrated that all four canonical memristor types can emerge in two-dimensional nanochannels, including two loop styles that had not previously been observed experimentally. A minimal model that combines ion–ion interactions with surface charge and entrance depletion reproduced these transitions and clarified how the same device family can be steered between volatile and non-volatile regimes. In this programmable setting, synapse-inspired dynamics such as short-term depression with recovery arise as a direct consequence of controlled ionic relaxation.[106]

These advances recast Ångström-scale slits as a chemically programmable substrate for ionic memory, where the internal state is encoded in correlated ion organization and interfacial kinetics rather than in simple double-layer charging. The ability to co-design polarity, volatility, and relaxation time through geometry and electrolyte chemistry provides a direct route from nanoscale physics to neuromorphic function, and suggests that arrays of atomic channels could serve as ultralow-power analogue elements for adaptive information processing.

3.3 Electrohydrodynamic memristors in confined channels

Another distinct mechanism for ionic memristors in hard nanofluidic systems involves fluid flow and moving interfaces. In these devices, memory resides not only in the ionic distribution but also in the physical position of a fluid boundary or meniscus that shifts under electrical bias. The operating principle typically relies on electroosmotic flow or electrowetting, whereby an applied voltage drives liquid to advance or recede within a channel, thereby modulating the conductive pathway. Hysteresis emerges when the interface position depends on the history of the applied voltage. For instance, a higher bias may displace the interface further, while upon voltage reduction or reversal, the interface may not immediately return to its initial position because of capillary forces or viscous dissipation. The resulting memristive response is governed by the fraction of the channel occupied by the conductive fluid relative to a nonconductive phase, which acts as the internal state variable.

A seminal example is the nanofluidic memristor based on an electrolyte–ionic liquid interface.[107,108] The device consisted of a nanochannel in PDMS connecting two reservoirs, with one filled with a KCl solution and the other with a hydrophobic ionic liquid immiscible with water (Fig. 8a). At equilibrium, the two fluids meet at the center of the channel, forming a well-defined meniscus. Applying a voltage induces competition between electroosmotic flow and interfacial tension, with one polarity advancing the aqueous-ionic liquid interface and the opposite polarity retracting it. The large contrast in ionic conductivity between the ionic liquid and the aqueous phase causes the channel conductance to depend on their relative occupancy. At intermediate states, the channel behaves as a variable resistor composed of a high-conductivity electrolyte segment in series with a low-conductivity ionic liquid segment. The interface motion was hysteretic, with viscous drag and meniscus energy barriers, including contact-angle hysteresis at the walls, preventing immediate relaxation after voltage removal or reversal. Accordingly, voltage sweeps exhibited pinched hysteresis loops, and the device could be programmed into multiple conductance states using voltage pulses of different magnitudes (Fig. 8b). The memristor showed excellent endurance and retention, as the negligible vapor pressure of the ionic liquid prevented drying or significant interfacial drift over time. In effect, the system behaves like a nanoscale electrical piston that drives a fluid boundary back and forth, with the piston position serving as the memory state.[107,108]

The hydrodynamic approach is appealing in that it leverages the inherently analog, continuum behavior of fluids. In principle,

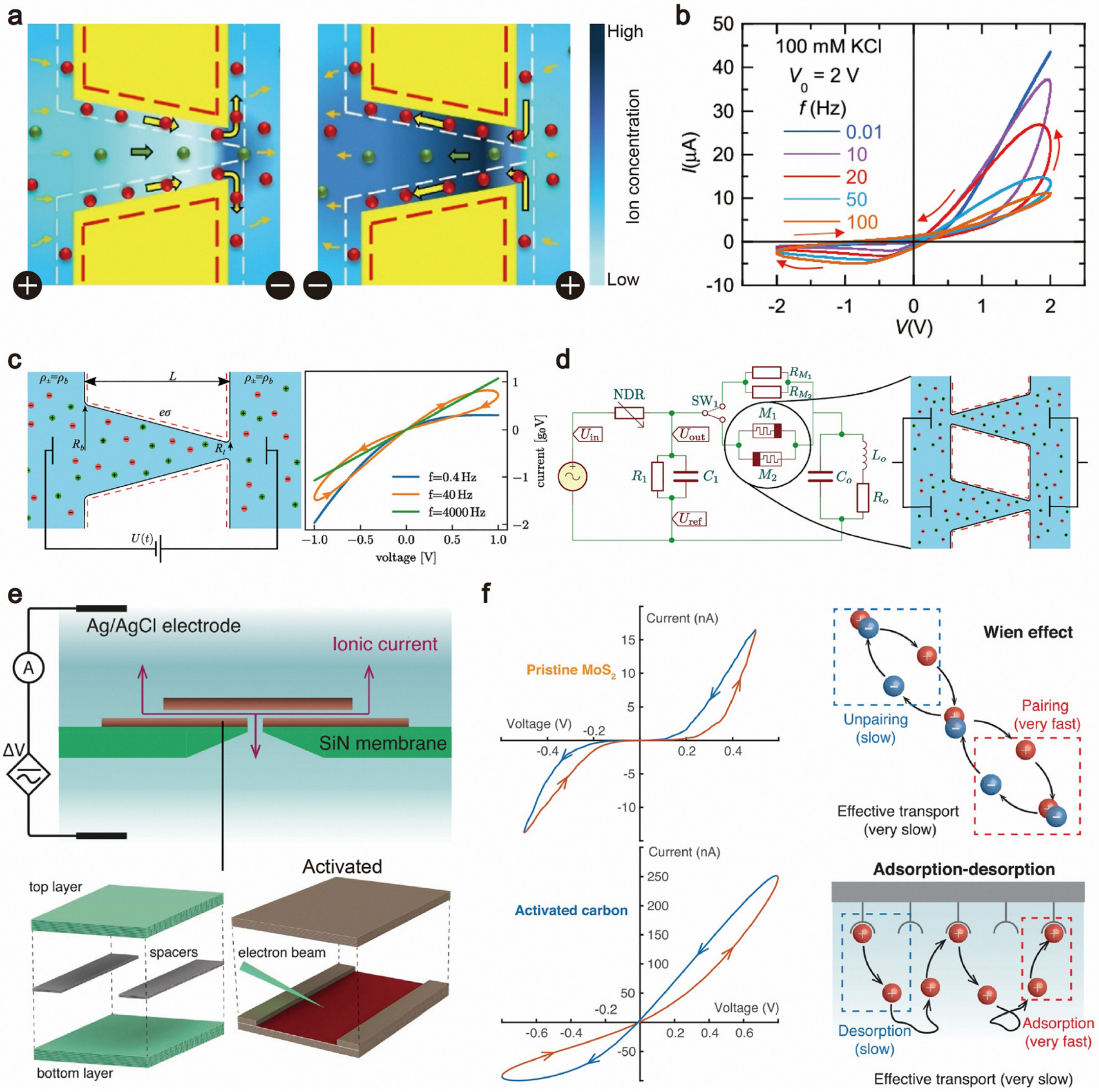

Fig. 7 Counterion dynamics- and deep confinement-derived ionic memristors. (a) Ionic concentration polarization at an asymmetric constriction, where bias-driven enrichment and depletion create a non-equilibrium ionic landscape that relaxes only slowly, imprinting history dependence on the conductance. Adapted with permission from ref. 86. Copyright 2024 American Chemical Society. (b) Pinched hysteresis loops in the current–voltage characteristics of a multipore conical nanopore membrane under sinusoidal driving, showing the frequency-dependent opening and closing of the memristive window as the drive period approaches the ionic relaxation time. Adapted with permission from ref. 19. Copyright 2023 American Chemical Society. (c) Minimal conical-pore model highlighting the role of access resistances and permselective enrichment/depletion zones in shaping rectification and hysteresis. (d) Circuit-level abstraction in which ionic memristors are treated as dynamical elements that can be embedded into neuromorphic signal-processing architectures. Adapted with permission from ref. 94. Copyright 2025 Creative Commons CC BY-NC 3.0. (e) Two-dimensional nanofluidic channels assembled from layered materials and locally activated to define angstrom-scale transport pathways. (f) Representative hysteresis in pristine MoS$_2$ and activated-carbon channels together with proposed microscopic origins of long-lived state variables, including field-enhanced ion-pair dissociation (Wien effect) and adsorption–desorption kinetics under strong confinement. Adapted with permission from ref. 105. Copyright 2023 The American Association for the Advancement of Science.

the meniscus position, and thus the device conductance, can assume a continuous range of values, enabling multilevel memory and gradual weight updates for neuromorphic computing. The approach embodies a trade-off between speed and retention: slow, inertial fluid motion limits switching speeds but enables nonvolatile memory by pinning the interface without power. This nonvolatility arises because, once displaced, the ionic liquid–aqueous interface remains pinned by capillary forces until a sufficiently large reverse bias is applied to overcome the pinning barrier. This is analogous to a mercury droplet in a capillary, which moves under pressure but remains pinned by surface tension until an opposing threshold is exceeded. Although fluid motion and interfacial deformation can dissipate energy, operation is often quasi-static, allowing the energy per switching event to remain low when distributed over time. Hydrodynamic memristors therefore occupy a unique regime in which mechanical and ionic degrees of freedom intersect.

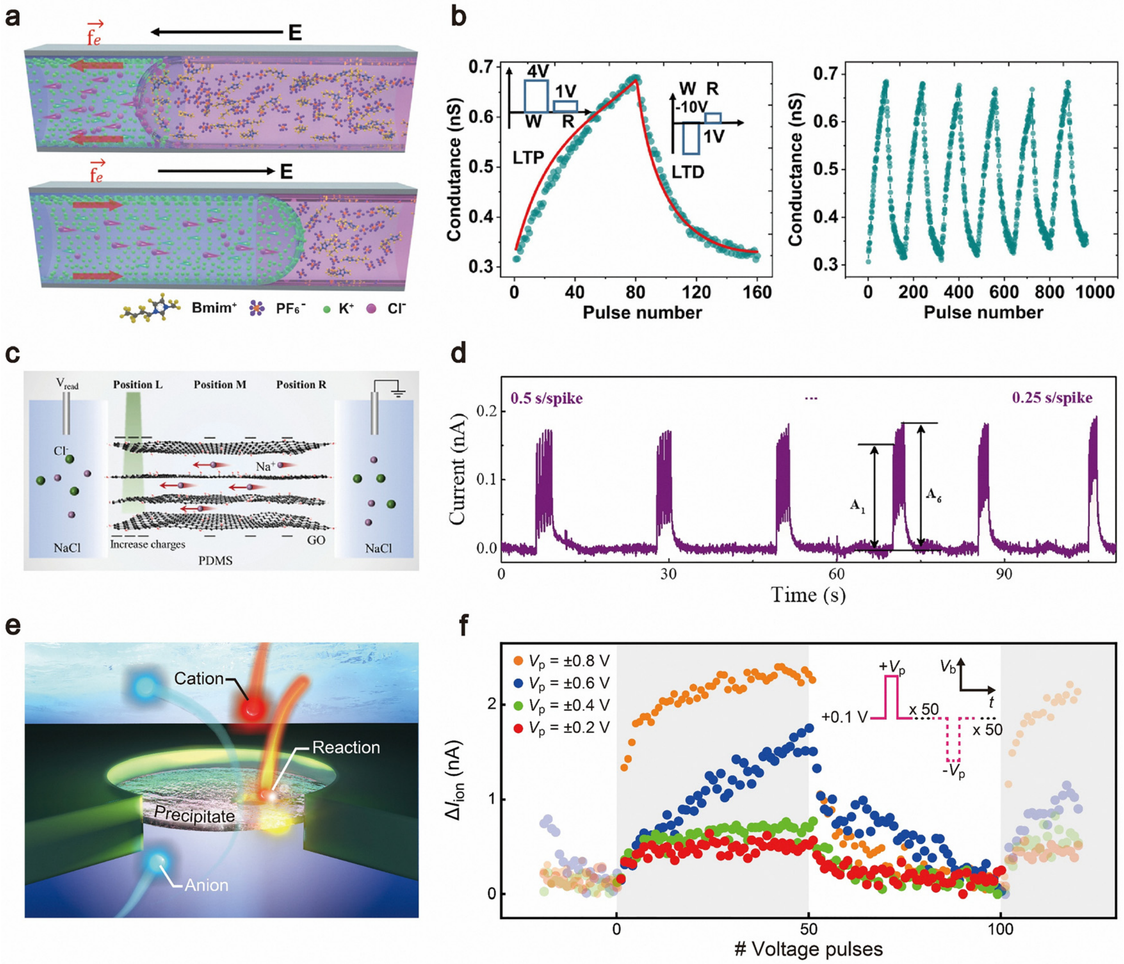

Fig. 8 Stimulus modalities for programming hard nanochannels. (a) and (b) An interfacial memristor formed by a nanochannel that bridges an aqueous KCl phase and an immiscible room-temperature ionic liquid (BmimPF6), where voltage-driven displacement of the liquid–liquid interface tunes ionic transport and supports analogue conductance updates. Adapted with permission from ref. 107. Copyright 2019 American Chemical Society. (c) and (d) Optogenetics-inspired nanofluidic artificial dendrite based on PDMS-coated layered graphene oxide. Localized light illumination generates an internal potential difference that drives Na^+ migration along lamellar nanochannels, producing position-addressable response currents and reconfigurable spiking. Adapted with permission from ref. 111. Copyright 2025 John Wiley and Sons. (e) and (f) Chemically gated pores in which transmembrane bias controls in-pore precipitation/dissolution chemistry, enabling pulse-programmable conductance states. Adapted with permission from ref. 120. Copyright 2025 Creative Commons CC-BY-NC-ND.

3.4 Optical programming and readout

Light offers a particularly clean handle for programming nanofluidic memristors. Unlike electrical gating, which requires dedicated wiring and electrodes for each element, optical stimuli can be delivered remotely, patterned in space and multiplexed in time. In optically gated devices, photons act as write pulses that reshape the ionic state though generating photovoltages, redistributing surface charge, or imposing local thermal/chemical gradients, while the resulting ion current provides an immediate read. This sensory-computing coupling echoes optogenetics in biology, although the state variable is not a protein conformation but the evolving distribution of ions and hydration shells within nanometer confinement.

Niu *et al.*[109] demonstrated a minimalist route to optical control by embedding a semiconductor heterojunction into a single nanopore. Upon illumination, the junction generated an additional photovoltage (tens of millivolts under their conditions), effectively turning the nanopore into a self-biased ionic pump. Under steady electrical bias, the ion current increased under light and tracked optical on–off modulation with a response time of about 50 ms, consistent with photocarriers creating an internal field that adds to, or subtracts from, the applied bias and therefore shifts the concentration-polarization state in and around the nanopore.[109]

Wang and colleagues[110] built an optically modulated nanofluidic ionic transistor using a metal-organic framework membrane grown within a porous anodic alumina template. The framework is intrinsically negatively charged, and illumination generates electron–hole pairs that transiently increase the negative surface charge of the metal–organic framework (MOF) crystallites, drawing additional cations into the tortuous pores. This photoinduced ion accumulation produces excitatory post-synaptic current-like transients, paired-pulse facilitation, and a pulse-history-dependent transition from short-term to longer-lived plasticity, as the relaxation time for cation release competes with the optical pulse interval. By using trains and patterns of light spikes to tune synaptic weight, the device reproduced higher-level behaviors such as learning-experience, Pavlovian associative learning, and optical Morse-code encoding/decoding, illustrating how optical addressability can be pushed beyond switching toward information processing within a single ionic element.[110]

An optogenetics-inspired design pushed optical addressability from a single pore to a dendrite-like nanofluidic element by embedding layered graphene oxide (GO) nanochannels in an elastomer (Fig. 8c).[111] Here, light creates an electric potential difference between illuminated and dark regions of the GO, driving directional Na^+ migration and producing pronounced ionic photocurrents. Because the optical input can be applied at different positions and in multiple spots, the device naturally supports distributed integration. It reproduced spatial summation with both sublinear and superlinear regimes, and it expressed temporal plasticity under trains of light spikes, including paired-pulse facilitation as well as spike-duration- and spike-rate-dependent conductance modulation. By combining spatiotemporal optical stimuli with ionic readout, the authors further demonstrated neuromorphic perception and a reflex-like output in a soft robotic actuator, emphasizing that optical control can move nanofluidic memristors beyond two-terminal switching toward computation within a single fluidic element (Fig. 8d).[111]

Mechanistic insight from atomically thin membranes provides a complementary perspective on how optical write operations might be converted into durable ionic memory. Molecular dynamics simulations of a subnanoporous two-dimensional membrane showed that synaptic-like plasticity can arise from competitive bicationic transport, where strongly adsorbed Na^+ transiently blocked permeation pathways that otherwise conducted K^+, and voltage spikes desorbed Na^+ to potentiate permeability.[112] Because adsorption and desorption introduce distinct time constants, the same structure can, in principle, interpolate between volatile and longer-lived states by tuning ion species, concentration, and stimulus waveform. Notably, the estimated energy cost per conductance update was in the attojoule range, highlighting why optical actuation, capable of delivering localized write pulses without parasitic leakage, may be especially attractive for scaling to large arrays. These studies suggest a general design rule for optical nanofluidic memristors: use light to impose a controllable internal photoelectric bias or a local thermal perturbation[113] that steers ion occupancy in confined junctions, and exploit the ensuing relaxation dynamics to encode computation in the ionic state.

3.5 In-pore chemistry and reaction-driven memory

In-pore chemistry offers a direct route to ionic memory, where the internal state is encoded in the local chemical composition and phase within the confined pore volume. Under transmembrane bias, electromigration and concentration polarization bring reactants into contact and drive reversible transformations, most prominently precipitation and dissolution, that open or obstruct the conduction pathway. Because the state evolves through reaction-diffusion kinetics rather than instantaneous electrostatics, the characteristic response time and retention can be tuned over orders of magnitude by pH, reactant concentration, multivalency, temperature, the stimulus waveform, and the confinement geometry. In practice, these levers allow the same physical platform to be pushed towards volatile short-term plasticity or long-lived, quasi-nonvolatile memory.

The origins of this concept can be traced to early observations of current instabilities caused by nanoconfined reactions. When two solutions mix within a nanopore, a transient precipitate was shown to repeatedly form and clear, producing oscillatory ionic currents.[114] The resulting nanoprecipitation in a nanopipette tip was demonstrated to be actively created and eliminated by switching the voltage polarity, enabling controlled blockage and recovery.[115] The earliest stages of nucleation and crystal growth through transient current blockades were tracked using a nanopipette platform.[116] Similar features were also observed from slow Ca^{2+} binding to charged pore walls.[117] These studies established that field-driven transport creates a reactive mixing zone whose evolving chemistry becomes the memory variable.

Liu *et al.*[118] demonstrated a complementary regime in conical nanopores, where reversible $CaHPO_4$ nanoprecipitation at the pore tip generates pronounced pinched hysteresis loops. Here, the memristive characteristics are set by precipitation and dissolution kinetics and can be tuned by $CaHPO_4$ concentration, voltage amplitude, and scan rate. Under pulsed stimulation, the conductance relaxes back once the stimulus is removed, yet remains robustly resettable, resembling short-term plasticity in biological synapses. This chemistry-driven volatility is attractive for temporal filtering and adaptive gain control, where forgetting is a feature rather than a limitation.[118]

Cho *et al.*[119] moved beyond hysteresis in the time-averaged conductance by encoding memory in the frequency of ion-current oscillations. In their conical nanopore, dynamic formation and removal of nanoprecipitates produce stochastic switching between high- and low-conductance states. The oscillation statistics depend on the direction of the voltage scan and on prior stimuli, appearing as a history-dependent open-state probability. Under programmed pulse trains, the device exhibits synaptic-like long-term potentiation and depression, consistent with delayed precipitate formation and clearing, together with slower drift in the effective space charge. A reduced description in which precipitation is limited by the cation arrival rate captures the emergence of oscillations and their bias-history dependence.[119]

A distinct solid-state implementation further advances this principle by imposing spatial control over the reaction zone, with anionic and cationic reactants supplied from opposite sides of a solid-state nanopore membrane.[120–122] One reservoir contains phosphate-buffered saline, whereas the opposite side supplies mobile cations from chloride salts (Fig. 8e).

The applied voltage drives these cations into the nanopore, where they encounter phosphate and reversibly form metal-phosphate precipitates that close the pore under one polarity and dissolve under the other. This voltage-gated in-pore chemistry yields extreme rectification and enables memristive switching at sub-nanowatt power (Fig. 8f). Because the gate is a reaction product, the dynamic response is, in principle, engineerable: pH controls phosphate speciation and solubility, reactant concentrations set supersaturation and nucleation rates, and the cation identity and temperature tune dissolution kinetics. These parameters offer a practical route to tune the balance between rapid, volatile switching and slowly relaxing states with extended retention.[45,119]

In-pore chemistry memristors expand nanofluidic memory beyond purely electrostatic hysteresis. By co-designing confinement with reaction kinetics, they provide a chemically programmable memory kernel whose volatility, retention and learning dynamics can be tuned using standard chemical control parameters.

4. Hybrid architectures: rigid scaffolds with soft ionic states

We now turn to hybrid architectures, in which rigid microfabricated scaffolds are deliberately paired with soft ionic elements. Their appeal is a clear functional split: the hard framework delivers geometric precision and addressability, while the soft phase introduces slow internal state variables, chemical selectivity and analogue adaptability.

Soft-hard hybrid nanofluidic systems combine rigid nanostructures, such as solid-state nanopores or nanochannels, with soft ionic components including polymers, gels, biomolecules, and fluids. Such hybrid architectures are designed to balance scalability, reproducibility, and integration offered by hard materials with the adaptive, history-dependent ionic dynamics characteristic of soft matter. From a neuromorphic standpoint, hybrid systems are especially attractive as they reflect the multiscale architecture of biological neural systems, where rigid structural elements coexist with soft, dynamically reconfigurable components. In artificial systems, this division of labor enables a fixed, manufacturable geometry while preserving fluid, reconfigurable degrees of freedom that underpin learning and memory.

In hybrid nanofluidic memristors, a solid-state scaffold fixes the transport geometry, providing well-defined channel dimensions, alignment, and connectivity. Such scaffolds can be fabricated using top-down nanofabrication methods compatible with wafer-scale processing, enabling high device uniformity and large-area array integration. Within this rigid framework, soft ionic components like ionic gels and biomolecules introduce internal state variables that evolve in response to electrical, mechanical, or chemical stimulation. Examples include polymer brushes grafted inside nanopores, ionic gels filling nanochannels, or biomolecules tethered to pore walls. These soft components modulate the ionic pathway through swelling, ion binding, conformational changes, or phase transitions while preserving their macroscopic geometries. As a result, device conductance becomes history-dependent not through permanent changes in channel geometry, but rather through memory encoded in the ionic microenvironment.

Soft-hard hybrid systems offer a key advantage by decoupling mechanical stability from functional plasticity. In purely soft systems, memory formation is often inseparable from mechanical deformation, which can lead to drift, fatigue, and limited reproducibility over extended operation. By contrast, purely hard systems typically rely on ionic redistribution or chemical transformations to achieve plasticity, which can restrict the diversity and adaptability of functional responses. Hybrid architectures circumvent both limitations. The rigid scaffold absorbs mechanical stress and preserves long-term structural integrity, while the soft component remains free to reorganize internally and encode memory. From a neuromorphic perspective, this feature can be similar to that in biology, where relatively stable axonal and dendritic scaffolds coexist with synapses whose efficacy is continually re-tuned by molecular reorganization. Such decoupling is particularly advantageous for long-term operation and training stability in neuromorphic hardware, as the learning element can undergo repeated adaptation without degrading the underlying device architecture.

Hybrid systems also naturally exhibit multiple memory timescales, a defining feature of biological cognition. Rapid ionic redistribution within the liquid phase gives rise to short-term plasticity, whereas slower processes, including ion binding, polymer relaxation, and reversible chemical reactions, govern long-term memory retention. Because these processes occur within a confined geometry defined by the solid scaffold, they can be precisely tuned through design parameters such as pore diameter, pore length, polymer density, grafting length, or electrolyte composition. This tunability potentially enables hybrid devices to emulate a broad spectrum of synaptic behaviors, ranging from volatile, stimulus-dependent responses to stable, non-volatile memory states. In neuromorphic computing, such multiscale plasticity is essential for implementing learning rules that require both transient adaptation and persistent weight updates, analogous to short-term facilitation and long-term potentiation in biological synapses.

In this section, we examine several representative classes of soft-hard hybrid nanofluidic systems, including ionic gel-filled nanopores, polymer brush-functionalized nanochannels, and other hybrid combinations. We emphasize how the interplay between mechanical rigidity and softness gives rise to memristive functionality, and how such designs address key challenges such as device stability, reproducibility, and integration density (Table 3).

4.1 Gel-filled nanopores and ionogels

One straightforward hybrid strategy involves filling or coating a solid-state nanopore or nanochannel with an ionic gel, such as a crosslinked polyelectrolyte or polymer electrolyte. In this

Table 3 Soft/hard hybrid systems with ionic memory

System class	Ref.	Material/fluidic system	Size	Mechanism	Stimulus class	Switching speed	Retention time	Energy consumption
Droplet/microchannel	54	Liquid–liquid interface microdroplet memristor in a microfluidic chip	1.5 mm long droplet	Voltage-driven droplet penetration into a microwell blocking/unblocking ion transport	Spike trains (10 V, 0.1 s); temperature used to modulate phase behavior	0.025–2.5 Hz	∼200 s	N/A
Ionic gel/microchannel	124	PDMS microchannels hosting bipolar polyelectrolyte gels, 10 mM KCl	Microchannel ∼2 mm × ∼500 μm; P- and N-gel lengths ∼1 mm each	Voltage-derived changes in depletion/accumulation zones of bipolar polyelectrolyte gels	Pulse trains (1 V, 4 s)	∼0.01 Hz	200–4000 s	N/A
Polymer brush/nanopore	130	Conical polyimide nanopore with dual-responsive PNIPAAm-co-AAc polymer brushes; 0.1 M KCl	Tip size ∼25 nm; base opening ∼1.2–1.5 μm	Stimuli-responsive conformation/charge state modulation of polymer brushes in channel	Environmental pH (3.6–9.4) and temperature; electrical *I–V* probing (±500 mV)	pH-induced rectification changes typically in minutes	N/A	N/A
Polymer brush/nanopipette	135	Glass nanopipette modified with polyimidazolium brush; 10 mM NaCl	Tip size ∼150 nm	Polyelectrolyte-confined ions undergoing strong ion–polymer interactions and slow reorganization	Environmental pH (3.6–9.4) and temperature; electrical *I–V* probing (±500 mV)	pH-induced rectification changes typically in minutes	∼500 ms	∼1 pJ per pulse
Ionic liquid/micropipette	136	PimB-modified glass micropipette interfacing $K_3Fe(CN)_6$ and KCl	Tip size ∼3 μm	Adsorption/desorption of ferricyanide switching surface charge and ionic selectivity/EOF in nanochannels	DC voltage 3 V	Oscillatory spiking: period ∼4.02 s (∼0.31 Hz); frequency tunable up to ∼18.7 Hz	Volatile/self-reset	N/A
Liposome/nanopore	141	SiN_x solid-state nanopore gated by nanoparticles/liposomes	Nanopore size 115 nm, liposome size hundreds nm	Nanoparticle trapping/release inside a nanopore changing effective aperture/resistance	Opening response ∼1.2 ms; closing response down to ∼0.3 s	N/A	∼10 nJ	N/A

configuration, the solid substrate, typically silicon, glass, or a mechanically robust polymer such as polyethylene terephthalate (PET), defines the channel geometry and ensures mechanical integrity, while the embedded ionic gel provides a continuous, non-volatile ionic medium whose internal dynamics can encode memory. The gels can be patterned at nanometer length scales, for instance, through localized photopolymerization within confined cavities, making them compatible with dense integration. They also mitigate practical issues associated with liquid electrolytes, including evaporation, nanobubble formation, and fluid displacement. In effect, the gel functions as a soft, adaptive core confined within a rigid nanofluidic shell, combining structural stability with dynamic ionic functionality.

A representative example is a track-etched PET membrane containing a conical nanopore that is filled with a salt-doped polyacrylamide hydrogel. In this hybrid structure, the conical nanopore provides a rigid, well-defined transport geometry, while the hydrogel introduces a soft, ionically active medium within the pore. Early work demonstrated that ionic current rectification in such conical nanopores is preserved after gel filling and that the gel can actively modulate the ionic response.[123] Extending this concept to memristive behavior becomes possible when the gel is made stimulus-responsive. For instance, if the gel contains charged functional groups, a strong electric field can locally deplete counterions and drive electro-osmotic water transport, leading to partial gel contraction. Upon reduction or reversal of the field, the gel does not instantaneously re-swell because of its viscoelastic relaxation, leaving the pore transiently more open or more obstructed than its initial state. This delayed swelling–deswelling cycle introduces a history dependence in the conductance, giving rise to hysteresis in the current–voltage characteristics. In this way, the internal relaxation dynamics in the soft matrix act as the memory variable, while the rigid nanopore confines and stabilizes the overall device geometry.

A more sophisticated realization of this concept is embodied in cascade hetero-gated gel systems for ionic modulation (Fig. 9a).[124] This approach envisions stacking or patterning multiple gels with distinct ionic properties within a single nanofluidic channel. Each gel layer functions as a history-dependent ionic gate, whose conductance evolves according to its own internal dynamics. For example, one layer may slowly accumulate protons and become more conductive under repeated stimulation, whereas another unit may preferentially expel ions or undergo partial deswelling, thereby reducing conductance. Arranged in series, therefore, these layers offer dynamically coupled barriers to ion transport, giving rise to complex hysteresis and rich temporal responses (Fig. 9b).[124] By confining the gels within a rigid channel, the

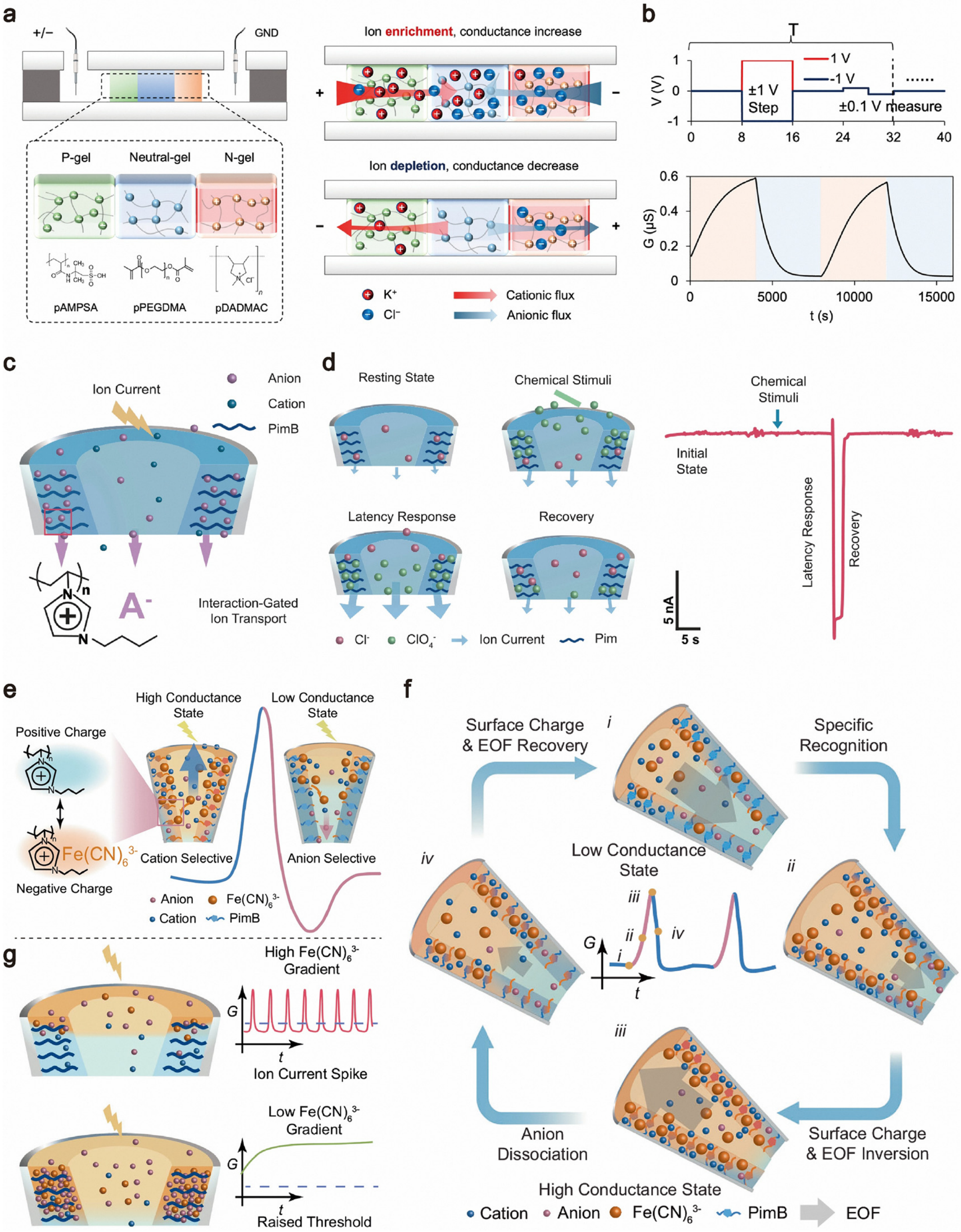

Fig. 9 Soft/hard hybrid fluidic systems carrying ionic memory into device-scale functions. (a) Architecture of an iontronic memristor in which a three-layer bipolar polyelectrolyte-gel stack. (b) Volatile-to-stable conductance dynamics under step programming and low-amplitude readout. Adapted with permission from ref. 124. Copyright 2024 Creative Commons CC-BY 4.0. (c) and (d) A polyelectrolyte-confined fluidic memristor converting molecular/ionic interactions into a history-dependent ionic conductance. Adapted with permission from ref. 135. Copyright 2023 American Association for the Advancement of Science. (e) and (f) Mechanistic cycle for autonomous spiking in a nanofluidic oscillating neuron. (g) Representative ion-current spike trains controlled by chemical gradients, showing repetitive firing and threshold modulation. Adapted with permission from ref. 136. Copyright 2025 Creative Commons CC-BY-NC.

overall geometry remains fixed, so that gel reconfiguration affects ionic pathways rather than deformation. From a neuromorphic perspective, such cascade architectures resemble multilayer synapses, in which distinct molecular processes operating on different time constants jointly regulate signal transmission and plasticity.

Ionic compositions can be engineered to tailor the dynamic ion transport characteristics. In this context, polyelectrolyte gels confined within nanopores have been explicitly highlighted as a promising platform for ionic memristors.[125] Their intrinsic nonlinearity, arising from ion–polymer interactions and swelling dynamics, naturally lends itself to memristive behavior. Furthermore, because the gels can host high concentrations of mobile charge, they enable relatively large ionic currents at low bias, easing impedance matching with electronic circuits compared with highly dilute liquid electrolytes. Experimental support for this concept comes from work[126] demonstrating that filling a micropipette tip with a fixed-charge polyelectrolyte gel produced inverted ionic current rectification and could mimic synaptic neurotransmitter release. Although this system was initially explored as a chemical delivery probe, the underlying mechanism could be extended to memristive operation. In particular, if the gel were engineered to retain ionic composition or charge distribution after stimulation, for example, through multicomponent ion doping or slow relaxation kinetics, the same architecture could encode memory in its transport response.[126]

Filling nanofluidic channels with gels also offers clear advantages for scalable integration. Arrays of nanopores can be fabricated on a single chip and subsequently filled in a single step by spin-coating or vacuum infiltration of a pre-gel solution, followed by curing. This approach is substantially simpler than individually addressing each pore with microfluidic plumbing and effectively solidifies the fluidic architecture into a mechanically robust device. The principal trade-off is a reduction in ionic mobility, since diffusion coefficients in gels are typically one to several orders of magnitude lower than in free solution, depending on polymer density and crosslinking.[127] However, for many neuromorphic computing tasks, where integration, memory retention, and analog weight evolution are more critical, such moderate operating speeds would be acceptable.[128]

Ionic gel-filled nanopores represent a compromise between the functional richness of liquid-based systems and the reliability of solid-state devices. They can reproduce key behaviors of purely fluidic architectures, such as threshold ion depletion and interfacial wetting transitions, while offering substantially improved mechanical stability and compatibility with large-scale integration. Challenges remain, including achieving homogeneous gel filling in ultrasmall pores, avoiding bubbles or void formation, and precisely controlling gel chemistry at the nanoscale. Nonetheless, continued advances in nanofabrication, polymer synthesis, and *in situ* curing strategies are likely to mitigate these limitations.

4.2 Polymer-brush nanochannels

A particularly elegant hybrid approach involves incorporating polymer brushes, consisting of densely tethered polymer chains, on channel walls. Instead of filling the entire space, a polymer brush coating on the surface enables dynamic tuning of the effective size, charge, and ionic selectivity.[129,130] Furthermore, polymer brushes are known to undergo conformational changes depending on the ionic environment, solvent quality, and pH.[131] They can also trap and release counterions in a hysteretic manner, for example when the brush contains multiple charge states or segments with differing ionic affinities.[132,133]

A notable example is the polyelectrolyte brush-confined ionic memristor,[134,135] consisting of a grafted layer of polyimidazolium chains inside a glass nanopipette (Fig. 9c). These brushes carry positive charges along their backbone, attracting anions. When a voltage was applied, the brush region could load up with anions, creating a high conductance state. Upon bias reversal, delayed anion release from the brush preserved elevated conductance, resulting in memristive hysteresis. In addition to synaptic functions, the device uniquely enabled chemical-electrical signal transduction, potentially allowing an artificial chemosensitive synapse for converting a chemical input into an electrical memristive signal (Fig. 9d–g). This example highlights a broader strength of brush-filled nanochannels through their rich chemical tunability. Polymer brushes can be engineered with functional groups that selectively respond to specific biomolecules or neurotransmitters.[136] For example, boronic acid–functionalized brushes can reversibly bind glucose, with transient concentration changes modulating conductance and imprinting a temporary chemical memory. Such chemically induced plasticity opens a route to devices that adapt in response to chemical signals or rewards, analogous to neuromodulation in biological neural systems, where neurotransmitters such as dopamine dynamically regulate synaptic strength.[135,137]

Another advantage of polymer brushes is their ability to respond across multiple timescales. At the molecular level, brushes can polarize extremely rapidly under local electric fields, as ions redistribute around individual polymer chains on nanosecond timescales. Concurrently, collective processes such as brush collapse or swelling unfold much more slowly, often over seconds. As a result, a brush-filled nanopore can exhibit both fast, transient changes in ionic current and slower, adaptive drifts in conductance. This intrinsic separation of timescales allows a single device to capture features of both short-term and long-term plasticity, integrating rapid responsiveness with persistent memory within the same physical element.[137]

In such hybrid architectures, the inorganic scaffold provides a mechanically robust framework with well-defined geometry, enabling a degree of device-to-device uniformity, while the polymer brush supplies the nonlinear ionic dynamics responsible for memory. Because the brushes are covalently tethered to the surface, they remain spatially confined and do not migrate or leach as free polymers might, leading to improved cycling stability.[135]

Polymer brush-filled nanochannels represent a rational hybrid design that merges the predictability of engineered surfaces with the adaptability of soft matter. They have enabled key advances, including chemical-to-electrical synaptic transduction, linking ionic memristors to chemical neuromodulation. By tuning brush chemistry and architecture such as charge type, grafting density, and chain length, the timescale and analog range of memristive behavior can be precisely controlled, with trade-offs between retention and response speed. At the nanoscale, polymer brushes serve as ionically active layers that endow rigid channels with memory and selectivity, where the solid scaffold provides mechanical stability and electrical interfacing, while the soft brush supplies ionic plasticity and chemical functionality essential for neuromorphic devices.

4.3 Stimuli-responsive polymer-filled nanopores

In general, the more manufacturable and dense the scaffold becomes, the harder it is to deliver a stimulus with the spatial precision and speed needed for truly addressable switching. A neat way around this is to move the active degree of freedom into a polymer inside the channel and trigger it remotely. In a recent thermoplasmonic design,[113] poly(*N*-isopropylacrylamide) brushes on the backside of a solid-state nanopore act as a temperature-responsive gate, swollen below the critical solution temperature to block ion passage, but collapsing when local heating pushes the pore above the transition, reopening the channel (Fig. 10a). What makes the approach feel distinctly nano-engineered is how the stimulus is delivered: a gold bullseye resonator concentrates the light illumination onto the nanopore aperture, producing rapid, reproducible temperature excursions and, in turn, robust ionic switching with on/off ratios up to around 60 over repeated cycles. Beyond proving the principle, the kinetics and addressability start to look

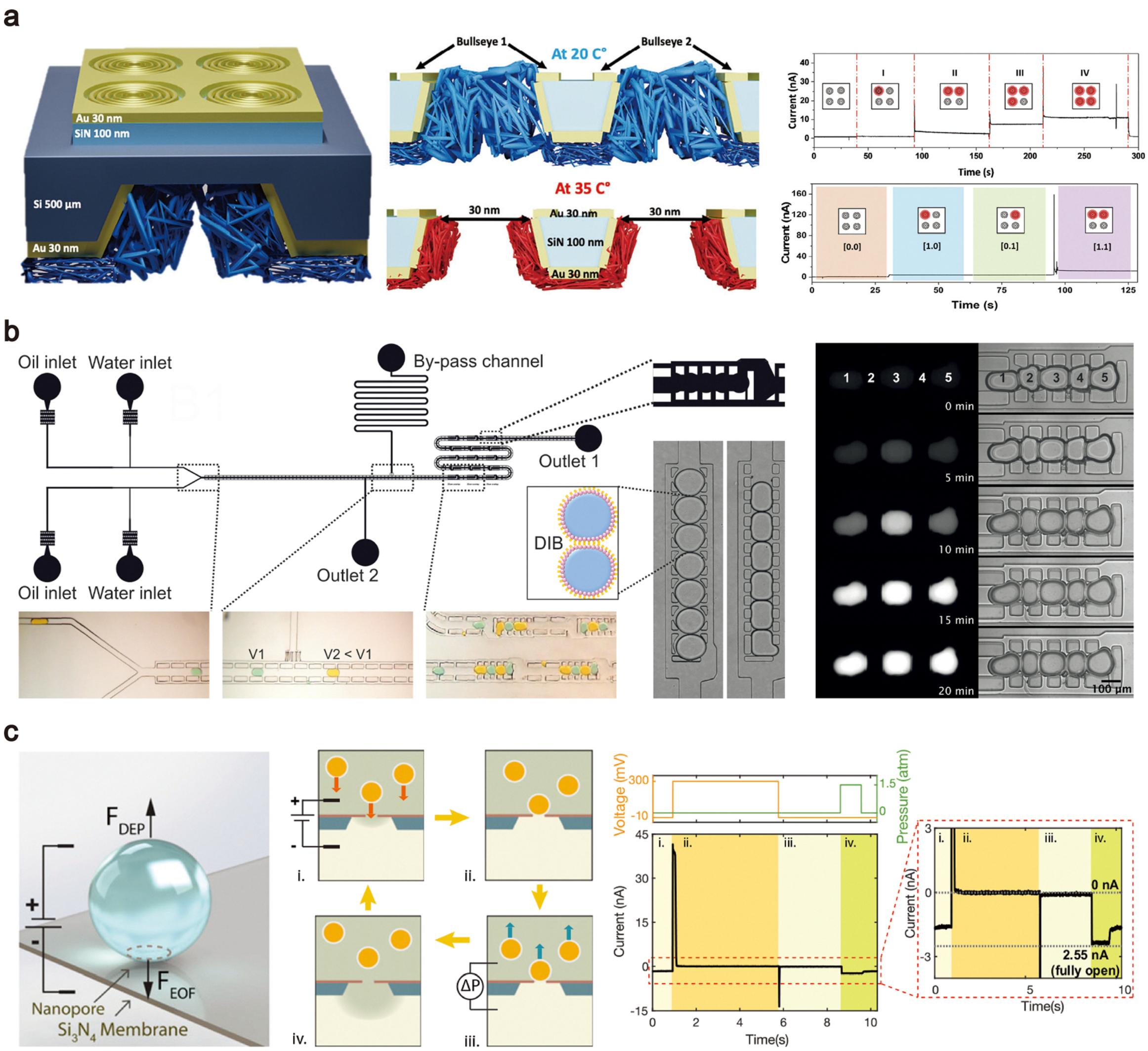

Fig. 10 Programmable gating at the soft–hard interface. (a) Thermoplasmonic optical gating of polymer-functionalized nanopores. A gold bullseye concentrates light illumination to locally heat PNIPAM above its critical solution temperature, selectively switching pores within an array with micrometer-scale addressability. Adapted with permission from ref. 113. Copyright 2025 Creative Commons CCBY-NC-ND 4.0. (b) A passive microfluidic shift-register architecture positions and stores trains of lipid-stabilized water-in-oil droplets. Adapted with permission from ref. 138. Copyright 2015 Creative Commons CC BY 4.0. Droplet contact self-assembles droplet-interface bilayers, enabling automated arrays for multiplexed assays. (c) Nanoparticle-blockage-mediated nanopore gating: rigid or soft nanoparticles are driven to a silicon nitride nanopore entrance to reversibly close the conduit in a ball-and-chain-like manner; small voltage or pressure stimuli yield millisecond response and complete closing. Adapted with permission from ref. 141. Copyright 2022 Creative Commons CC BY-NC-ND.

device-relevant, where rise/fall times of a few milliseconds were achieved, approaching the kilohertz regime of the conductance switching operation. Because the laser spot can be diffraction-limited to below 1 μm, individual pores in an array can be selected and orchestrated into simple current-based logic (Fig. 10b), turning a polymer-filled nanochannel from a single switch into an optically programmable ionic circuit element.[113]

4.4 Droplet-on-chip systems

Another hybrid strategy integrates droplet interface bilayers into solid microfluidic or electronic frameworks (Fig. 10c and d). In this approach, aqueous droplets are positioned in microfabricated wells on a chip, where lipid bilayers form reproducibly between adjacent droplets.[138] The solid substrate supplies electrodes, fluidic confinement, and addressing infrastructure, while the soft bilayers host the ionic processes responsible for computation.[55] By arranging multiple droplet pairs into patterned networks, it becomes possible to construct hybrid wet neural circuits that remain physically robust and electrically addressable. Early demonstrations have used techniques such as microdroplet printing to generate arrays of droplet interface bilayers with reasonable reproducibility.[139] A central challenge remains long-term stability, as bilayers are prone to rupture or drift over time, including partial gelation of droplets or polymer encapsulation have shown promise in mitigating these issues. If such stabilization can be achieved reliably, this architecture could enable large-scale arrays of memristive synapses on a single chip, with each droplet pair functioning as an individual, addressable synaptic element.

4.5 Nanoparticle-trapped nanopores

Another hybrid strategy involves embedding nanoparticles or nanoscale inclusions within fluidic channels to introduce field-responsive internal degrees of freedom. For instance, in a conical nanopore, a confined nanoparticle or soft inclusion, such as a protein aggregate or nanoscale droplet, can deform, or reconfigure under an applied bias, thereby modulating ionic transport. It was demonstrated that introducing SiO_2 nanoparticles into a conical nanopore led to elastic deformation-mediated memristive hysteresis, arising from the coupled motion of the particle and the surrounding ionic flow.[140] Although the nanoparticle itself may be mechanically rigid, its mobility within the fluid effectively creates a composite system in which a hard scaffold hosts a dynamically reconfigurable internal phase. This illustrates how embedding responsive nanoscale objects within otherwise rigid nanofluidic channels provides an additional route to memristive behavior, by coupling ionic transport to the history-dependent dynamics of an internal phase.

A deformable nanoscale vesicle can function as a plug that couples a nanopore conductance with memory. Yazbeck *et al.*[141] demonstrated that liposomes driven into a solid-state pore will irreversibly block ionic flow until a stimulus removes them (Fig. 10e). Under a modest electric field, a charged liposome is electrophoretically sucked into the pore and elastically deforms to seal it, achieving near-100% current blockade (Fig. 10f). Noticeably, the occlusion remains even after the voltage is turned off, enabling a nonvolatile memory effect, because the soft vesicle wedges in place rather than diffusing away. A brief pressure pulse can eject the vesicle, reopening the pore, which then persists until the next voltage stimulus. This nanoparticle-blockage gating is highly repeatable and tunable, effectively emulating a voltage-controlled ionic switch with volatile *vs.* nonvolatile memory determined by its softness. The key is that the inherent flexibility and surface adhesion give the system a built-in memory of its last blocked or unblocked state.[141]

4.6 Bio-hybrid systems

Perhaps the most fascinating hybrids involve actual biological components integrated with artificial ones. An example is growing living neurons on a solid-state ionic device so that they form a closed-loop hybrid network. The ionic memristor might receive neurotransmitter from the neuron and feedback an ionic current that stimulates the neuron, making a neuron-artificial-synapse hybrid. Early work has interfaced neurons with iontronic devices where the device can release ions like K^+ to trigger neural signals.[126] As we refine these interfaces, we may effectively bolt an artificial memristor in place of a missing synapse in a neural circuit, a true hard/soft hybrid synapse.

4.7 Summary of hybrid strategies

Soft materials, particularly droplet interface bilayers and lipid membranes, offer exquisite biomimicry and dynamic behavior but are often fragile and difficult to scale. Hard materials, such as conical nanopores etched in silicon or polymer substrates, afford integration and reproducibility but can struggle to encode complex ionic histories.[142] To bridge this divide, researchers are increasingly turning to hybrid systems, combinations of soft ionic elements embedded within rigid scaffolds, that blend the best of both approaches. This section illustrates the emerging strategy, highlighting devices where ionic gels, polymer brushes, or embedded nanoparticles introduce memory functions within hard geometries. These designs leverage multi-timescale ionic dynamics, chemical specificity, and tunable conductance, while maintaining the mechanical integrity and addressability needed for circuit integration. The interplay of materials in such hybrids enables rich functionality: polymer brushes permit chemical learning, ionic gels stabilize device geometry while encoding plasticity, and embedded particles offer new routes to responsiveness.

Overall, these hybrid architectures suggest a design paradigm where complexity is compositional. Rather than seeking a single material solution, engineers are building layered systems that mimic biological synapses as mechanically stable, yet chemically and electrically dynamic. This modular approach is paving the way for scalable iontronic platforms that retain the nuance of soft matter while embracing the precision of microfabrication. As the field advances, these hybrids are poised not just to supplement but to define future nanofluidic computing systems, embodying a pragmatic, multifaceted strategy for combining softness with scale.

5. From devices to ionic circuits

This section makes the system-level progression explicit, moving from single memristive junctions to coupled logic elements and then to small iontronic networks so the boundary between device physics and circuit-level function remains clear. Connecting multiple nanofluidic memristors into circuits is a necessary step beyond single-device phenomena, because networked ionic memory elements can display collective dynamics and computational capability that are not accessible in isolated devices.

Beyond digital logic, ion-driven circuits are being explored in which coordinated ionic dynamics naturally emerge. Conical nanopore memristors integrated into nonlinear oscillator circuits have been shown to exhibit alternating chaotic and periodic oscillations reminiscent of neural network dynamics (Fig. 11a).[143] Coupling three such ionic conductors demonstrated purely ionic XOR and NAND logic gates to a neural network,[94,101] and thus the potential to realize a complete set of logic operations using only memristors and simple electrical components (Fig. 11b). Here, ionic currents in one element entrain or modulate others, with the electrolyte itself serving as the communication medium. Mutual electrolyte coupling thus allows one memristor to modulate another state, analogous to synaptic gating in neural networks. Even in passive structures, similar coupling effects arise, as ordered nanopore arrays exhibit pore–pore transport interference due to overlapping diffusion layers and shared ion depletion zones. In other words, ionic transport through one pore can modify local concentration and electric field profiles sufficiently to gate the conductance of neighboring pores. Collective effects are enhanced by close proximity or shared reservoirs and can be exploited for computation.[89]

A landmark demonstration involved an ionic logic gate formed by two memristive nanopores coupled through a resistor (Fig. 11c).[23] Here, each nanopore modulated the voltage experienced by the other, enabling mutual gating and conditional switching analogous to electronic logic. The circuit realized a material implication gate, a Boolean primitive from which all other logic gates can be derived. This result showed unequivocally that computation can be implemented in ionic circuits using ions in solution without electronic carriers. Despite operating on second-long timescales, the demonstration established that basic computing primitives can be realized solely with nanofluidic memristors. Importantly, the two memristors in the material implication (IMP) gate were not isolated but interacted through the shared circuit, allowing each device to influence the state of the other.[23] Electrolyte-coupled interactions mark recurrent, state-dependent dynamics even in simple two-element networks.

Another striking manifestation is in chemical reaction-mediated memristors: in single nanopores, cyclical precipitation and dissolution of ionic solids can produce self-oscillating currents.[119,121] If multiple memristive pores governed by such in-pore reactions were coupled, their oscillations could synchronize in a manner analogous to coupled chemical oscillators. Networked nanofluidic memristors can thus exhibit new dynamical modes, from sustained oscillations to chaotic switching, expanding the computational repertoire of iontronic circuits.

Theoretical models support the promise of small ionic memristor networks for neuromorphic function. Brownian dynamics simulations by Noh *et al.*[112] showed that just a handful of coupled nanofluidic memristors can reproduce neuron-like spiking behavior. In their model, quasi-2D slit nanopores with memristive conductance were connected in a circuit analog of an integrate-and-fire neuron, and the collective ionic dynamics generated action potential-like voltage spikes.[112] There is also work demonstrated an all-ionic leaky integrate-and-fire oscillator using conical nanopore memristors and a resistor, which could fire repetitive spikes analogous to neural oscillations.[144] Notably, these designs achieved neuron functionality with far fewer components than an equivalent electronic circuit: a direct outcome of the rich physics within each ionic memristor like electric double-layer rearrangement, ionic adsorption, or concentration polarization. These theoretical findings suggest that ionic memristor networks could inherently perform neuromorphic tasks such as pattern generation and potentially even learning with minimal circuitry.

The prospect of ionic memory circuits also opens intriguing possibilities for bio-interfacing. Because they use the same carriers as biology, arrays of ionic memristors might seamlessly interface with living neural tissue. One could imagine an implantable iontronic chip where each memristor responds to local biochemical signals and drives an electronic feedback to neurons, effectively communicating in the native ionic language in the brain.[145,146] Such hybrid soft-hard systems would blur the boundary between computing devices and biology, leveraging the biocompatibility and soft mechanics of fluidic components.

Assessing the potential and limitations of multi-memristor nanofluidic circuits makes it clear that the field remains at a very early stage. The integration scale today is on the order of only 2–3 devices working in concert, compared to the billions of transistors in modern electronic chips, effectively the iontronic analogue of early electronic computer prototypes from the 1940s. Scaling these systems to large, reliable circuits is challenging, as ionic devices are orders of magnitude slower than semiconductor switches and long-distance ionic transport is limited by diffusion and fluidic resistance. The requirement for specific liquid environments or isolation further complicates large-scale integration of nanofluidic memristors.

Concerns also remain regarding manufacturability and uniformity, as nanofluidic elements are likely to show greater device-to-device variability in geometry or surface chemistry than semiconductor transistors. Nonetheless, a tangible path forward is emerging: modern micro- and nanofabrication techniques enable the creation of nanochannel and nanopore arrays with high precision, and recent studies have begun to exploit these capabilities. For example, some of the memristive nanopore devices were fabricated in a scalable way on silicon nitride chips, yielding dozens of working devices that could potentially be addressed in parallel.[119] Likewise, two-dimen-

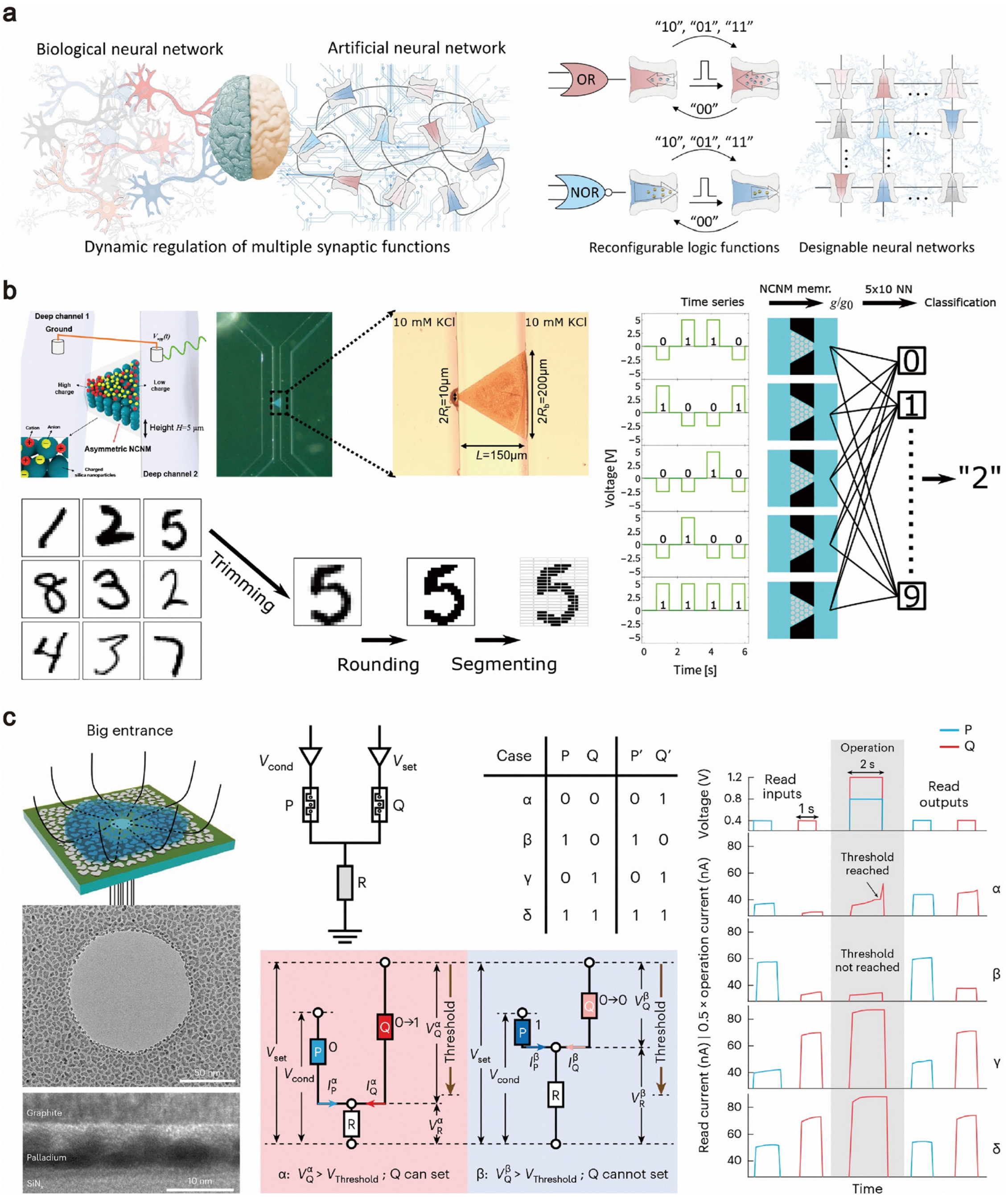

Fig. 11 Iontronic circuits and learning architectures. (a) Single-pore nanofluidic logic memristors leverage ion enrichment/depletion states that coevolve with chemical cues and voltage history to implement reconfigurable synaptic functions and logic, while programmable series/parallel interconnects scale these elements into multi-memristor assemblies and small neural networks. Adapted with permission from ref. 143. Copyright 2024 American Chemical Society. (b) Tapered microchannels embedding a colloidal nanochannel-network membrane generate volatile yet reproducible conductance dynamics through transient salt concentration polarization, such that handwritten digits encoded as input time series are mapped onto channel responses and classified with a simple readout layer. Adapted with permission from ref. 101. Copyright 2024 Creative Commons CC BY 4.0. (c) Circuit-scale nanofluidic logic using mechano-ionic memristive switches. Highly asymmetric channels are designed for in-memory processing and can be assembled into logic circuits composed of two interactive devices and an ohmic resistor. Adapted with permission from ref. 23. Copyright 2024 Creative Commons CC BY.

sional nanochannel memristors have been demonstrated on-chip, showing that multiple fluidic memories can coexist and even be tuned individually by adjusting their local electrolyte conditions.[106] As a result, one can envision a future ionic integrated circuit comprising many memristors arranged in a network, analogous to a crossbar of artificial synapses. In practice, large-scale iontronic processors are therefore expected to adopt hybrid architectures, in which electrodes and wiring are used to interconnect and control arrays of fluidic devices organized into modular units. Signal readout and interfacing present an additional challenge, as ionic currents must be converted to electronic signals at some stage. Ultimately, although scaling iontronic circuits to very large-scale integration (VLSI) complexity is an ambitious goal, the rewards are considerable. Large networks of ionic memristors would operate in regimes of ultra-low power and inherent parallelism, potentially achieving brain-like efficiencies. They could be directly merged with chemical and biological processes, enabling forms of soft computing in environments where silicon chips falter. In the coming years, it is anticipated that the field will transition from one-off device physics demonstrations to developing the design principles and architectures for multi-memristor ionic circuits. By analogy with the evolution of electronic computing, rudimentary iontronic gates and synapses may become the foundational building blocks of future ion-based intelligent machines.

6. Prospects and challenges

Nanofluidic memristors have proven their ability to emulate synapses and neural circuits in concept, but transforming these laboratory devices into practical, large-scale neuromorphic systems comes with significant challenges. In this section, we outline the key hurdles and prospects for the field, including device integration, scalability and switching speed. Each of these factors could limit performance or reliability if not addressed, yet each also offers opportunities for innovation. Whereas many of the challenges for ionic memristors are shared with those faced by traditional electronics, there are also issues unique to iontronics, such as water drying and slow ionic mobility. The prospects, on the other hand, include leveraging the intrinsic advantages of ionic systems such as super-efficient energy usage and inherent biocompatibility to create computing platforms that could profoundly impact both technology and bioengineering.

6.1 Thermal management

Thermal management is an inevitable issue in integrated circuits.[147] While ionic memristors operate at extremely low energy per event, often in the femtojoule to picojoule range, the challenge of thermal management becomes significant when scaling to large arrays or increasing switching speed. Efforts to accelerate switching by increasing ion concentrations or bias voltages can introduce ohmic heating.[148–150] Heat accumulation should be mitigated as it can lead to evaporation, bubble formation, ion mobility drift, and degradation of soft materials like lipid bilayers or polymer brushes. In this regard, nanoscale channels offer limited paths for heat dissipation. Solutions include using thermally conductive substrates, pulsed operation to allow for passive cooling, or microfluidic circulation of electrolytes. Designs inspired by the brain, *i.e.*, short sparse spikes and distributed computation, help minimize local heating. The goal can be cold computing that functions at room temperature without active cooling. The brain remains a blueprint with minimal energy per event, distributed load, and graceful operation. Achieving this in engineered iontronics requires both material innovation and rethinking how we compute.

6.2 Ionic fatigue

Like metals under repeated stress, ionic memristors face degradation from cyclic ion migration and associated chemical or mechanical changes, a phenomenon termed ionic fatigue. This can manifest as reduced hysteresis, drift in resistance states, or complete failure due to fouling, delamination, or irreversible reactions. For example, side reactions, such as unintended water electrolysis, can alter pH and surface charge, degrading materials like polyelectrolytes or brushes over time. Ion depletion or irreversible trapping, especially in systems relying on finite ionic species, can exhaust switching capacity. Mechanical effects like swelling, drying, or interfacial stress can also fracture gels, rupture membranes, or wear down soft layers.

Mitigating fatigue demands chemically stable architectures, minimizing reactive species, and confining operation to regimes that avoid extreme ionic or pH excursions. Some soft materials offer self-healing like hydrogels with dynamic bonds that can restore structure and conductivity after damage.[151] Another strategy is to reserve volatile switching for frequent activity while limiting non-volatile writes, analogous to dynamic random access memory (RAM) refresh or memory consolidation in the brain.

Still, more complex architectures, especially those involving redox-active components or porous frameworks, may face increased susceptibility. As in batteries, long-term retention may come at the cost of reversibility or responsiveness. Balancing endurance with plasticity thus remains an open design challenge.

Meanwhile, several devices already exhibit excellent endurance. Zhang *et al.*[107] report ionic liquid system remaining stable over many cycles, likely due to its non-volatile medium and reversible interfacial motion.[107] A molecular brush-confined device also maintained performance through extensive cycling, owing to robust covalent attachment and non-consumptive ion interactions.[136] With careful chemistry, mechanical robustness, and thoughtful operation, future ionic devices could achieve lifetimes rivaling solid-state transistors while retaining the unique dynamics of soft, ion-driven systems.

6.3 Mechanical stability

Mechanical fragility is a key challenge for nanofluidic memristors, especially those incorporating soft matter such as lipid bilayers, hydrogels, or droplets. These components are vulnerable to deformation, drying, and rupture under environmental stress, limiting device durability. Long-term deformation, such as hydrogel creep or nanopore etching, can shift device baselines, necessitating recalibration. Emulsion-based systems offer one route to enhanced mechanical stability through droplet miniaturization and self-stabilization. Equally important is packaging: maintaining hydration and shielding devices from contamination can dramatically extend operational lifetimes. Hybrid strategies like polymer-stabilized bilayers, hydrogel encapsulation, and soft-hard integration offer enhanced mechanical integrity. As fabrication techniques mature, ionic devices are expected to become as mechanically reliable as conventional electronic components.

6.4 Device integration scalability

Scaling nanofluidic memristors from lab prototypes to large-scale systems remains a core challenge. Unlike electronics, where lithography processes enable to integrate billions of transistors, ionic systems require managing liquids, interfaces, and ion transport across many channels, thereby posing distinct architectural and fabrication hurdles. Device arrays are feasible *via* microfabrication, since nanopores or nanochannels can now be defined with sub-100 nm precision. Early demonstrations of multi-memristor layouts suggest scalable ionic circuits are within reach.[106] Further refinements can pursue crossbar nanopore junction architectures as an analogue of the resistive random access memory (RRAM) configurations that could enable dense, addressable ionic memristor arrays (Fig. 12a). Key to this is integrating electrode networks

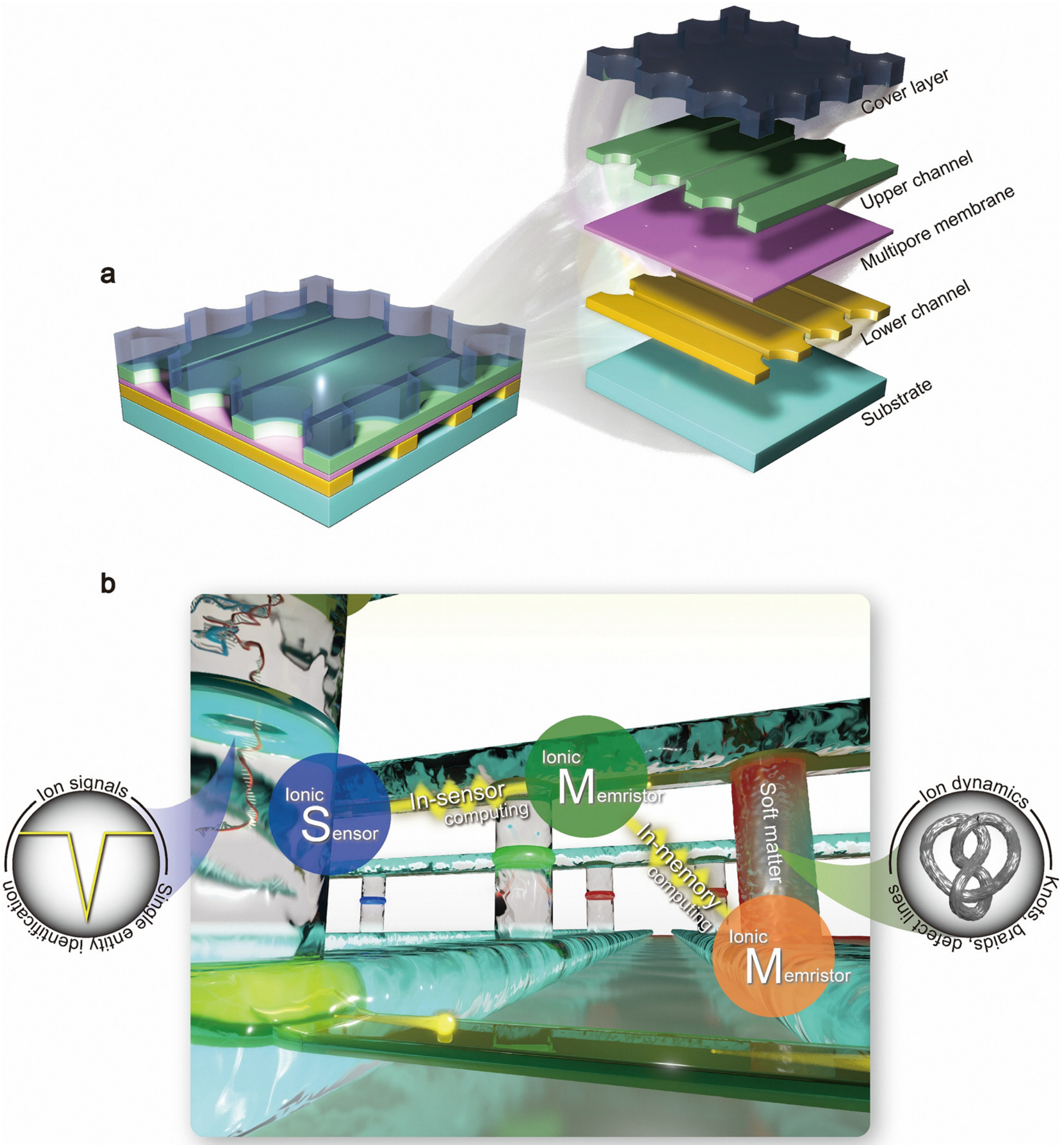

Fig. 12 Crossbar nanopore junction system. (a) Schematic of a crossbar architecture in which row and column fluidic channels are patterned on opposite sides of a multipore membrane, so that each channel intersection defines an individually addressable nanopore junction. Selecting a specific row-column pair localizes the applied bias and ionic flux to the corresponding junction, enabling dense, addressable ionic memristor arrays in a layout analogous to crossbar RRAM. Expanded view of the stacked implementation (cover layer, upper channel layer, multipore membrane, lower channel layer, and substrate) illustrates a manufacturable route to scaling nanopore-junction devices with simplified interconnect routing and on-chip integration. (b) Conceptual nanopore-junction architecture for in-sensor and in-memory computing each addressable junction senses ionic events while nearby adaptive conductance stores local context, enabling in-sensor classification and in-memory computing with analogue ionic weights.

for local gating, and optimizing designs for functional scalability, where few devices can perform complex logic.

A complementary route to scalability would be to view integration not only as adding more devices, but as increasing the function per junction. For example, an addressable array can operate as a co-integrated sensor/memory fabric, where each junction performs nanopore sensing[152–154] while neighboring junctions store and update conductance states that retain local context. This architecture naturally supports in-sensor computing, where raw translocation pulses are classified directly at the sensing site, or in-memory computing, where the adaptive ionic conductance acts as an analog weight so that computation proceeds where the state is stored rather than shuttling signals across slow diffusive ionic paths. Ionic polymers would provide a practical materials bridge for this co-integration, where polymer brushes, gels, and other confined polyelectrolytes add tunable chemical selectivity and multi-timescale internal state variables that stabilize memory while remaining compatible with hard nanofabricated nanopores and channels. Further advances in the state engineering may also be achievable by exploiting soft matter[67] in which information is stored not only in ion concentrations but also in reconfigurable spatial patterns, such as arrays of line defects as well as knotted and braided filamentary structures, that create a large accessible space of stable configurations and transitions for robust,[155,156] low-power physical information processing. In this view, scalable iontronic systems will likely emerge as modular networks of sensor/memristor nodes, coupled by short-range ionic dynamics for rich analog processing and by electronic interconnects for long-range communication (Fig. 12b).

At the system level, the most credible near-term architecture is an ion–electron co-processor. Ionic junctions are well suited to local state evolution, analogue weighting, and chemically coupled adaptation, whereas electronic amplifiers, multiplexers, and complementary metal–oxide–semiconductor (CMOS) circuitry remain superior for addressing, signal conditioning, and long-range communication. The central engineering task is therefore not to replace electronics outright, but to build low-leakage interfaces that preserve slow ionic state dynamics while enabling fast and stable readout. This same logic extends to neural interfaces, where soft conductive composites and hydrogel-based conductors can reduce mechanical mismatch with tissue while providing reliable ion–electron transduction.

To approach brain-like computation with many interacting ionic weights, multiple ionic memristors should be organized as a cross-bar nanopore-junction array in which orthogonal fluidic or electronically addressed word lines and bit lines intersect at individually defined nanopore junctions. Each cross-point then functions as a local ionic synapse, where the applied row/column bias sets the transmembrane field across that nanopore, the junction conductance stores the synaptic weight, and the summed current collected along a shared line naturally implements the fan-in operation required for analogue vector-matrix multiplication. In this architecture, short-range ionic coupling can support local state adaptation and history-dependent learning, whereas electronic selectors, amplifiers, or gate electrodes should handle addressing, isolation, and long-range communication so that write/read operations remain stable despite the slower relaxation of ions. A practical brain-inspired implementation is therefore not a purely ionic network, but a hierarchical ion–electron system in which dense crossbar nanopore junctions provide massively parallel adaptive weighting while surrounding circuitry orchestrates timing, multiplexing, and error control.

6.5 Switching speed

The rate at which ionic memristors change state is constrained by the inherent slowness of ion transport compared to electrons. While ionic memristors will not rival the GHz speed of electronic transistors, their efficiency and analog capabilities position them for applications where millisecond precision and energy-saving characteristics outweigh clock frequency.

Typical ionic devices switch at rates from hertz to kilohertz, with some reports of nanopore-based memristors reaching 100 kHz. Such speeds, though modest, are sufficient for many sensory and learning tasks. Further speed enhancement may be possible by device miniaturization through shorter channels for smaller droplets to reduce ion transit times. Pulsed or high-field operation may also transiently accelerate switching, albeit with trade-offs in energy efficiency and stability. Volatility also shapes speed. Fast, volatile devices offer quick response but poor retention, while stable, non-volatile ones tend to switch slowly. Adjusting volatility or pairing ionic elements with electronic drivers may optimize speed for specific tasks. Parallelism provides a system-level workaround. Massive arrays of slower devices operating concurrently, similar to the brain architecture, can deliver high throughput despite modest individual speeds. This model suits neuromorphic inference at biologically relevant timescales.

7. Conclusions

Table 4 shows the emerging landscape of memristive memory into a single cross-platform benchmark. By placing soft, solid-state nanofluidic and hybrid ionic systems alongside conventional electronic memristors, it makes the governing trade-offs transparent across write energy, switching time, retention, on/off ratio and scalability. Soft ionic platforms occupy the corner of highest physicochemical richness, lowest energy cost and closest compatibility with biological media. Solid-state nanofluidic and hybrid architectures, in contrast, sacrifice some of that freedom to gain reproducible geometry, addressability and routes to manufacturable integration. Electronic memristors remain unrivalled in raw switching speed and industrial maturity,[157–160] yet their internal state is typically less entangled with chemistry, hydration and multiscale relaxation; features that give ionic platforms distinctive leverage for adaptive, life-adjacent computing.

Seen in this way, fluidic and solid-state memristors are better understood as points along a continuum than as competing

Table 4 Benchmark ranges across ionic and electronic memristive platforms

System class	Energy consumption	Switching speed	Retention time	Integration/scalability
Soft fluidics	10 aJ–pJ	ms–s	ms–hours	Low to moderate
Hard fluidics	fJ–pJ	μs–ms	s–hours	Moderate
Soft/hard hybrid fluidics	10 aJ–pJ	μs–ms	ms–days	Moderate to high
Electronic memristors (RRAM/CMOS)	pJ–nJ	ns–μs	days–years	Very high

categories. Soft fluidics operate in the most biomimetic regime, where memory is inseparable from chemical environment and mechanical compliance, although this same coupling can amplify drift and slow dynamics as systems scale. Hard nanofluidic devices move closer to the engineering logic of semiconductor hardware by fixing geometry and compressing the active volume, while preserving the central premise of ionic intelligence: information is stored and processed in liquid-phase ionic distributions rather than in electronic carriers within solids. Hybrid devices offer the most practical bridge between these regimes, combining wafer-compatible scaffolds with fluid-like internal state variables and thereby providing a credible route towards large-scale ion–electron co-integration. Framed in this way, benchmarking is not a matter of deciding which platform wins, but of mapping complementary operating regimes and identifying the design opportunities that arise when computation is allowed to be both electrical and chemical.

Nanofluidic memristors embody a convergence of chemistry, biology, and electronics, defining a new class of devices where ions, not electrons, serve as the fundamental carriers of information. Throughout this review, we have seen how harnessing ion transport in confined fluids enables rich, synapse-like behaviors, *i.e.*, history-dependent conductance, short- and long-term plasticity, and the integration of electrical and chemical signaling within a single device. By operating with ions rather than electrons, these memristors mimic the signaling mechanisms of biological neural networks, offering prospects for brain-like energy efficiency and inherent biocompatibility. Proof-of-concept devices already exhibit a diverse array of functions, from droplet-based synapses capable of learning and forgetting, to solid-state nanopores executing logic with liquid blister memories, to polymer brush-lined nanochannels that transduce chemical cues into electrical responses. These advances point toward an emerging iontronics, where information is processed through flowing electrolytes, rather than within rigid semiconductor lattices.

Yet, realizing the full promise of ionic memristors for artificial intelligence applications will require continued innovation to overcome the challenges. Thermal management should ensure that these devices, often operating in aqueous environments, remain cool and stable even as we scale up integration. Materials and designs need to be refined to prevent ionic fatigue so that devices can learn and re-learn over billions of cycles without degrading. The delicate soft components of many ionic devices require reinforcement through hybrid architectures and packaging to guarantee mechanical stability in real-world operating conditions. Perhaps most critically, methods to integrate large arrays of ionic memristors, bridging the gap from single demonstrators to dense networks, will determine whether ionic computing can move from a laboratory to practical deployment.

A balanced assessment also requires identifying the regimes in which each platform is likely to thrive, and those in which its limitations become fundamental. Soft devices are unparalleled in biocompatibility, compliance and chemically rich state dynamics, but remain susceptible to dehydration, drift and limited clock speed. Solid-state nanofluidic devices offer tighter control over geometry and stronger prospects for large-scale fabrication, although their memory can be diminished at high ionic strength when double-layer contrast is screened. Hybrid architectures widen the design window by combining robust scaffolds with adaptive ionic materials, but they introduce their own interfacial challenges, including delamination, solvent loss and packaging complexity. These boundaries are not weaknesses to be hidden, but design constraints that should inform platform choice for neural interfaces, soft robotics, sensing and on-chip analogue learning.

In terms of performance, ionic memristors should not be erected to rival the gigahertz switching of transistors as they do not need to. Their comparative advantage lies in energy efficiency and rich functionality rather than raw speed. As multiple studies have highlighted, these fluidic devices can operate at femtojoule or picojoule energy scales per event, approaching the unmatched efficiency of the human brain. Furthermore, they inherently support analog storage and computation within the same medium, eliminating the artificial separation of memory and processing that plagues von Neumann electronic architectures. For AI-tasks like pattern recognition, sensory processing, and adaptive control, ionic memristor networks are particularly well suited. Indeed, as we build chips with thousands of ionic synapses operating in parallel, we may find that despite slower individual devices, the overall system throughput for AI computations is competitive with or even superior to conventional approaches, all while consuming orders of magnitude less power.

The road ahead for nanofluidic memristors will likely see increased synergy with other emerging technologies. We anticipate hybrid platforms where ionic memristor cores interface with CMOS control circuits, bridging the best of both worlds, the ion–electron hybrid computers that use electrons for communication and ions for computation. On the algorithmic front, researchers will explore how to exploit the multivariate nature of ionic signals to implement novel forms of computation that have no easy electronic analog.

Nanofluidic memristors bring us a significant step closer to the vision of brain-like artificial intelligence hardware: systems that are not only low-power and highly parallel, but also adaptive, self-organizing, and intimately linked to the chemical and ionic processes of life. As these devices mature, we foresee them becoming central components in next-generation AI as in-memory analog computing units on chips, soft neuromorphic robots, brain-interface prosthetics, and beyond. Ionic intelligence remains in its infancy, yet current progress outlines a compelling trajectory toward a new computing paradigm rooted in ion and fluid physics, with the potential to seamlessly bridge artificial systems and biological function.

Over the next decade, progress will likely be shaped by four priorities. First, multi-ion and multi-channel devices should move beyond single-species memory to access the richer, state-dependent dynamics that support neuron-like behavior. Second, scalable ion–electron co-integration will be essential, with dense ionic arrays coupled to CMOS backplanes that provide addressing, low-noise current-to-voltage conversion, and high-bandwidth readout and control, approach already established in CMOS-integrated nanopore front ends and in analyses of bandwidth/noise constraints in ionic recordings.[161] Third, new materials platforms, including soft conductive composites and chemically programmable interfaces, should improve stability without sacrificing the chemically coupled functionality that makes iontronic state variables distinctive. Fourth, the field needs shared benchmarking standards for endurance, retention, environmental robustness and energy per update, enabling meaningful comparisons across platforms and accelerating translation. Progress along these axes will determine whether ionic intelligence remains an intriguing laboratory concept or matures into a practical hardware platform, especially as mixed ionic–electronic transducers provide a direct bridge from ionic state variables to electronic signals suitable for long-range routing and CMOS-compatible processing.[162,163] If successful, nanofluidic memristors could become primary members of the future integrated circuits family, powering a revolution in computing as profound as the advent of the semiconductor era, but this time driven by the dance of ions in nanoconfinements.

Conflicts of interest

There are no conflicts to declare.

Data availability

This Review article does not report new experimental or computational data. Data sharing is not applicable to this work. Any data discussed or re-plotted in figures are available in the cited primary literature.

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