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Iontronic logic control driven by dynamic electrical double layer regulation

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Abstract

Logic control underpins modern computation, sensing, and information processing, yet conventional semiconductor systems, despite their speed, integration density, and stability, remain limited by high energy demand, restricted memory plasticity, and poor biocompatibility. This Perspective introduces iontronic logic control as a next-generation paradigm in which ions act as information carriers for programmable signal processing. Logic control can be implemented through ion-concentration gradients, mechanically induced ionic migration, and dynamic regulation of electrical double layers (EDLs) at interfaces under applied fields. Critically, at dielectric interfaces where no external bias is imposed, localized triboelectric fields generated through contact electrification enable electrostatic regulation of EDLs, coupling mechanical-energy harvesting with real-time logic-state modulation. This mechanism facilitates robust ionic-electronic interactions without external power input. Within such an energy-information flow framework, iontronic logic achieves ultralow-power signal processing, intrinsic memory and plasticity, and reliable operation in aqueous and bio-relevant environments. Representative systems operate with millisecond-level or faster response times and energy consumption in the nanowatt range or even self-powered performance under triboelectric or concentration-gradient excitation. These capabilities open pathways to flexible, self-powered, and bio-integrated information systems that transcend the fundamental constraints of traditional semiconductor electronics.

Keywords: Iontronic logic control, electrical double layer, dynamic regulation, ultralow-power signal processing, energy-information flow

INTRODUCTION

Logic control is a fundamental component of modern information technology, governing how signals are processed, stored, and converted into executable decisions[1-3]. It supports a broad spectrum of applications, including cloud computing[4], autonomous robotics[5], large-scale environmental sensor networks[6], and biomedical diagnostic systems[7]. Many of these emerging information platforms operate as distributed, intermittently powered nodes that must function over long durations in aqueous or biological environments[8-10]. These conditions impose stringent demands on the logic elements themselves, requiring ultralow energy consumption to enable autonomous operation or compatibility with harvested power sources[11], memory plasticity for adaptive processing and long-term data retention without frequent refreshing[12,13], and intrinsic biocompatibility to ensure stable, non-fouling performance in ionic or physiological media[14,15]. As a result, the performance metrics of logic systems are being redefined: the traditional emphasis on speed and integration density is shifting toward energy efficiency, adaptive memory behavior, and seamless integration with biological settings.

A variety of platforms have been established for implementing logic control, each offering distinct operational advantages, as summarized in Figure 1. Complementary metal-oxide-semiconductor (CMOS) technology remains the dominant paradigm, providing ultrafast switching speeds, high integration density, and exceptional operational stability, and serving as the foundation of contemporary digital electronics[16] [Figure 1A]. Photonic logic offers ultrafast response and robust stability, making it well-suited for high-bandwidth and low-latency information processing[17] [Figure 1B]. Molecular logic devices provide inherent biocompatibility and notable memory capacity, enabled by the chemical tunability of their molecular building blocks[18] [Figure 1C]. Spintronic platforms integrate relatively high switching speeds with improved energy efficiency by exploiting electron spin rather than charge transport[19] [Figure 1D]. Quantum logic architectures leverage superposition and entanglement to achieve rapid computation and intrinsic memory retention[20] [Figure 1E]. Collectively, these approaches have each played a pivotal role in advancing the landscape of logic control. However, the rise of distributed sensor networks, biointegrated electronics, and long-term autonomous systems is redefining the functional requirements of logic elements. These emerging technologies, particularly in brain-machine and human-machine interfaces, demand components that combine ultralow energy consumption with intrinsic memory plasticity and robust biocompatibility, capabilities that no single existing platform can fully deliver[21,22]. In this context, iontronic logic control has emerged as a compelling alternative[23] [Figure 1F]. By using ions as dynamic information carriers and exploiting the electrochemical characteristics of solid-liquid interfaces, iontronic systems inherently combine ultralow energy consumption, adaptive memory behavior, and natural compatibility with biological and aqueous environments, positioning them as a strong candidate for next-generation logic technologies.

As summarized in Table 1, iontronic logic exhibits several decisive advantages that distinguish it from conventional logic control methods. Firstly, it features high energy efficiency and intrinsic energy-information integration. Unlike traditional solid-state architectures that rely on external electrical or optical power inputs, iontronic logic can directly couple energy flow to information flow through ion-concentration gradients, mechanical excitation, or dynamic modulation of the electrical double layer (EDL). Such coupling allows the same physical process to simultaneously govern energy harvesting and signal transduction, enabling self-sustained or self-powered operation. Secondly, iontronic logic demonstrates adaptive and analog memory behavior, arising from the reconfigurable ionic distributions and interfacial polarization within dynamic EDLs. This mechanism provides tunable synapse-like plasticity and history-dependent signal modulation, offering a matter-based route to learning and adaptive computation. Thirdly, the intrinsic biocompatibility and environmental adaptability of iontronic systems, stemming from their use

Table 1. Comparison of characteristics of different logic control methods

Indicator	CMOS logic	Photonic logic	Molecular logic	Spintronic logic	Quantum logic	Iontronic logic
Signal carrier	Electrons	Photons	Molecules/ ions	Electron spin	Quantum states	Ions
Energy efficiency	Good	Limited	Limited	Excellent	Limited	Excellent
Response speed	Excellent	Excellent	Limited	Excellent	Excellent	Good
Integration level	Excellent	Good	Limited	Good	Limited	Good
Stability	Excellent	Excellent	Good	Good	Limited	Good
Adaptive memory	Limited	Limited	Good	Good	Good	Excellent
Biocompatibility	Limited	Good	Excellent	Limited	Limited	Excellent
Operational medium	Solid state	Optical cavity	Aqueous/ organic	Solid state	Cryogenic	Aqueous/ biological
Representative advantage	Speed & scalability	Bandwidth & latency	Chemical tunability	Energy efficiency	Quantum parallelism	Higher energy efficiency, adaptive memory, and biocompatibility

CMOS: Complementary metal-oxide-semiconductor.

of aqueous electrolytes and ionic carriers naturally aligned with physiological environments, make them ideal candidates for seamless integration with bioelectronic and neural interfaces. Collectively, these attributes underscore the potential of iontronic logic as a transformative platform that unifies energy harvesting, information processing, and intelligent adaptability within a single physical framework.

MAIN TEXT

Iontronic logic driven by ion-concentration gradients and mechanical stimuli

Early demonstrations of iontronic logic showed that ionic migration can simultaneously serve as the charge carrier for both energy delivery and information flow. A representative strategy utilized reverse electrodialysis driven by ion-concentration gradients to establish a fully ionic power source, enabling the operation of microfluidic logic components [Figure 2A]. Alternating cation- and anion-exchange membranes generated voltages of approximately 2 V, powering polyelectrolyte diodes and OR logic gates in aqueous media[23]. Real-time fluorescence imaging confirmed that the logic outputs originated from the redistribution of mobile ions, while simple mechanical constriction of a compliant electrolyte tube functioned as a variable resistor, enabling on/off switching and stepwise potential control without any electronic circuitry. Expanding upon the concept of ion-concentration-gradient-driven power generation, a more recent study integrated this principle with ion-selective nanofluidics to achieve enhanced performance. A Janus MXene membrane with oppositely charged layers forms sub-nanometer channels exhibiting bidirectional ion permselectivity [Figure 2B], simultaneously enhancing ionic current and voltage under salinity differences[24]. Molecular dynamics simulations revealed partial dehydration and selective binding of multivalent ions, facilitating efficient monovalent ion transport and achieving record power densities. Leveraging this gradient-driven MXene platform, researchers constructed an iontronic transistor capable of switching between cut-off, linear, and saturation regimes merely by exchanging the source and drain electrolytes, thereby directly coupling concentration-gradient power generation to logic-level signal modulation. This work represents the first conceptualization and experimental realization of two-dimensional (2D) iontronic logic based on 2D nanofluidic materials, enabling direct control of robotic actuation.

Despite these advances, approaches that depend exclusively on liquid-phase ion-concentration gradients face significant practical challenges, including the need for precise membrane fabrication and rigorous sealing to preserve concentration differentials and prevent cross-leakage between reservoirs. Moreover, the

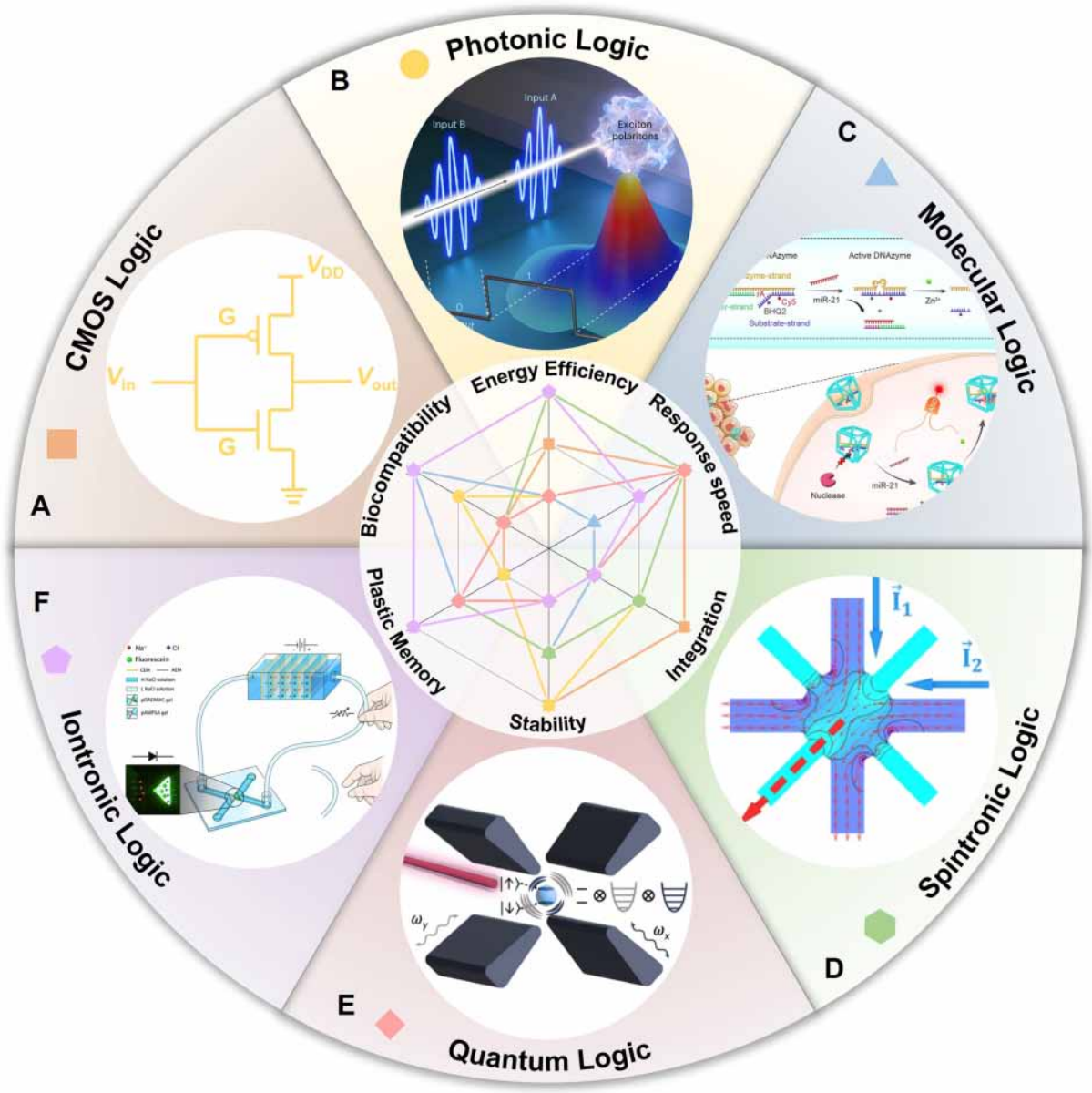

Figure 1. Representative platforms for implementing logic control. (A) CMOS logic; (B) Photonic logic. This figure is quoted with permission from the authors[17]; (C) Molecular logic. This figure is quoted with permission from Wiley-VCH GmbH[18]; (D) Spintronic logic. This figure is quoted with permission from the authors[19]; (E) Quantum logic. This figure is quoted with permission from the authors[20]; (F) Iontronic logic. This figure is quoted with permission from the authors[23]. CMOS: Complementary metal-oxide-semiconductor; BHQ2: black hole quencher 2; Cy5: cyanine 5; miR-21: microRNA-21; AND: AND gate; CEM: cation exchange membrane; AEM: anion exchange membrane.

reliance on liquid electrolytes limits portability, making such systems unsuitable for powering portable electronics and rendering them sensitive to temperature fluctuations and evaporation. These constraints have spurred the search for alternative mechanisms capable of driving ionic migration without sustained chemical gradients or complex fluidic confinement. Addressing this challenge, a parallel line of research has shown that purely mechanical actuation can directly induce ionic motion via the piezoionic effect, offering a robust and gradient-free route to ion transport[25] [Figure 2C]. Geometrically asymmetric polyacrylamide hydrogels containing mobile salts converted applied pressure gradients into directional ion flux and voltage

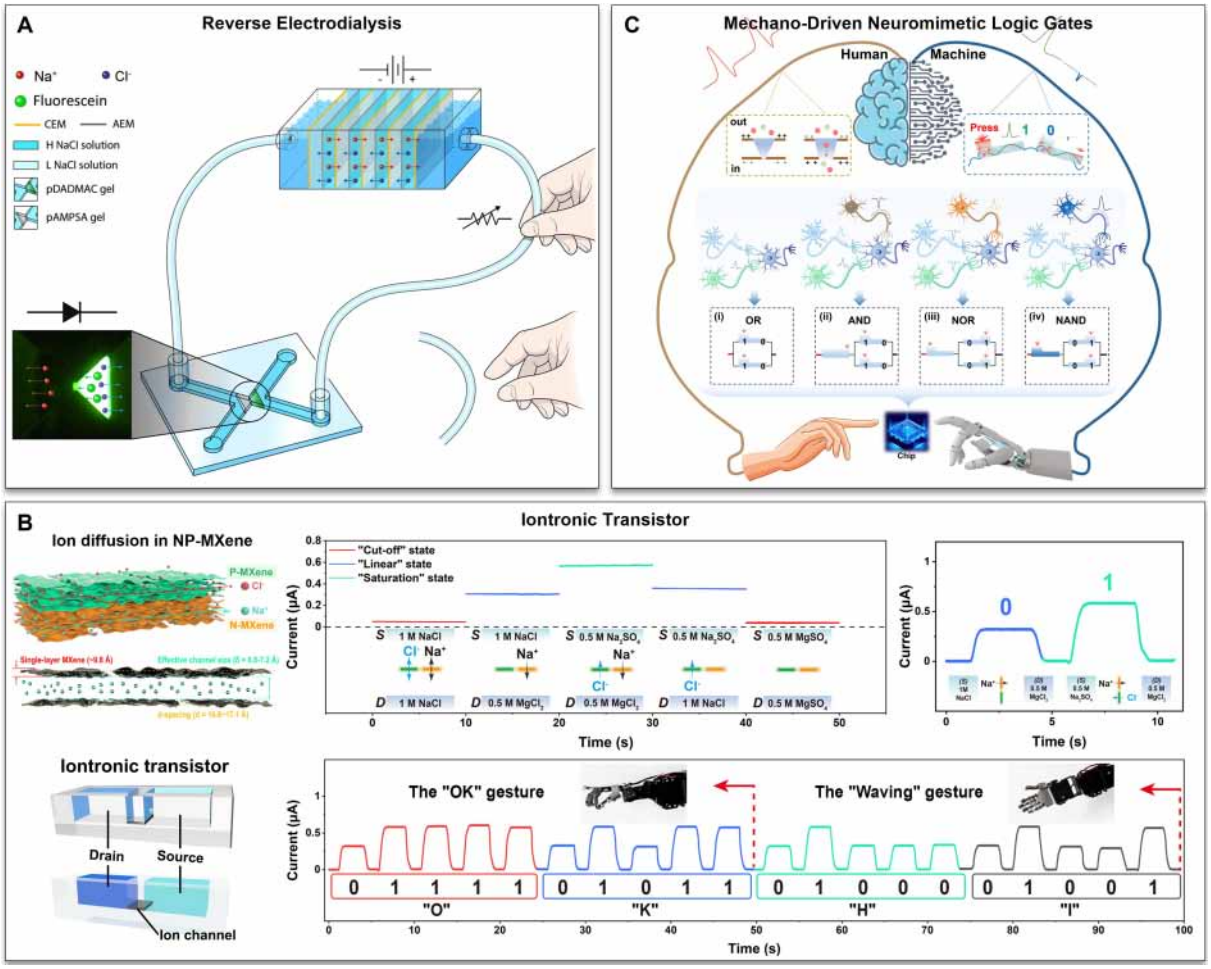

Figure 2. Iontronic logic driven by ion-concentration gradients and mechanical stimuli. (A) The logic device via reverse electrodialysis. This figure is quoted with permission from the authors[23]; (B) The logic control via integration of ion-concentration gradient and ion-selective nanofluidics. This figure is quoted with permission from the authors[24]; (C) Mechano-driven neuromimetic logic gates could realize OR, AND, NOR, and NAND logic gates operating solely on mechanical stimuli. This figure is quoted with permission from Wiley-VCH GmbH[25]. NOR: NOT OR gate; NAND: NOT AND gate; NP-MXene: nitrogen-phosphorus MXene; CEM: cation exchange membrane; AEM: anion exchange membrane.

spikes. By configuring these hydrogels in series and parallel, researchers realized OR, AND, NOR (NOT OR), and NAND (NOT AND) logic gates operating solely on mechanical stimuli. Output spikes exceeding predefined thresholds defined digital states, while tuning ionic species, concentration, and actuation frequency enabled control over signal polarity and memory-like behaviors reminiscent of synaptic integration. Collectively, these studies demonstrate that ion-concentration gradients and mechanical deformation can independently or synergistically drive precise ionic migration to implement logic functions[24,25]. They establish foundational principles of energy harvesting, selective ion transport, and mechanical regulation that inform subsequent advances in iontronic logic, laying the conceptual and practical groundwork for the next generation of low-power, adaptive, and biocompatible computing systems.

Iontronic logic driven by dynamic regulation of EDLs at conductive interfaces

While ion-concentration-gradient and mechanically driven approaches demonstrate that ionic transport can encode logic without external electronics, they inherently rely on maintaining salinity gradients or

mechanical actuation, complicating device sealing, scalability, and long-term stability[26,27]. To address these limitations and enable precisely controllable, electronically addressable logic operations, researchers have focused on the EDL at conductive interfaces. This approach allows direct gating of ionic motion through a small applied voltage, facilitating rapid switching, fine programmability, and inherent compatibility with aqueous and biological environments[28,29]. When a potential is applied across a conductor-liquid interface, the Gouy-Chapman-Stern (GCS) EDL reorganizes: counterions form a compact Stern layer adjacent to the electrode, while a diffuse layer of mobile ions screens the surface charge[30] [Figure 3A]. The interfacial capacitance, represented as the series combination of these layers, can be continuously tuned by the external bias. Such dynamic modulation of surface charge density, ionic composition, and local potential provides a direct, low-power mechanism to gate ionic current, allowing the interface itself to function as a reconfigurable logic element without requiring permanent chemical gradients or mechanical actuation. Over the past several decades, traditional electrochemical principles have been applied to create field-effect transistor-based sensors such as chemical field-effect transistors (ChemFETs) and ion-sensitive field-effect transistors (ISFETs), enabling precise, voltage-controlled ionic detection and modulation[31,32]. A ChemFET operates analogously to a conventional metal-oxide-semiconductor field-effect transistor (MOSFET) but replaces the metal gate with a chemically responsive membrane. When the concentration of a target analyte changes, specific receptor molecules embedded in this membrane bind the analyte and alter the local surface potential, thereby modulating the channel current. The resulting current variation reflects the concentration gradient established across the sensing membrane, which provides selective recognition of the analyte. An ISFET is designed to measure the concentration of specific ions in solution and likewise follows the basic operating principle of a MOSFET, except that the metal gate is substituted by an ion-sensitive membrane, an electrolyte solution, and a reference electrode[33,34]. Variations in ionic activity, such as changes in H^+ concentration (pH), modify the surface potential at the membrane/electrolyte interface and, consequently, the transistor channel current[35]. Widely regarded as the first generation of biologically sensitive field-effect transistors (BioFETs), ISFETs established the foundation for a broad range of biochemical and medical sensing technologies. These devices exploit the dynamic regulation of the EDL to achieve precise control over ion transport, enabling logic operations without the need for continuous chemical gradients or complex mechanical architectures. Consequently, they hold significant promise for integration into portable, low-power electronic systems. Taken together, these pioneering devices demonstrate how electrochemical gating can be seamlessly combined with solid-state electronics, providing a robust platform for iontronic logic functions and paving the way for the development of portable, energy-efficient, and biologically compatible computing systems.

Recent studies underscore the versatility of this approach, iontronic logic driven by dynamic regulation of EDLs at conductive interfaces, across diverse device architectures. For instance, vertical organic electrochemical transistors incorporate porous ionic channels coupled with cationic polyelectrolyte gates, achieving millisecond-scale switching bias of less than 2 V[36] [Figure 3B]. Precise engineering of the drain geometry modulates ionic penetration and the spatial distribution of the EDL, enabling gate-voltage-driven dedoping of the polymer channel to achieve both high-gain Boolean operations and synaptic plasticity analogous to biological junctions. Similarly, gel-polymer electrolyte ionic diodes utilize asymmetric solid electrolytes sandwiched between fluorine-doped tin oxide electrodes [Figure 3C]. Application of modest external potentials reorganizes interfacial ions to form or collapse depletion layers, producing high rectification ratios and enabling OR and AND logic gates that maintain stable operation across a broad temperature range from -20 to 125 °C[37]. At the nanoscale, single-pore nanofluidic logic memristors employ voltage pulses to protonate or deprotonate surface groups, reversibly altering surface charge and thus the EDL profile within the pore[38]. This mechanism supports multi-level conductance states, enabling reconfigurable logic and in-memory computing with synapse-like learning rules[39] [Figure 3D]. Likewise, nanofluidic ionic transistors demonstrate outstanding ionic gating behavior[40] [Figure 3E]. By modulating

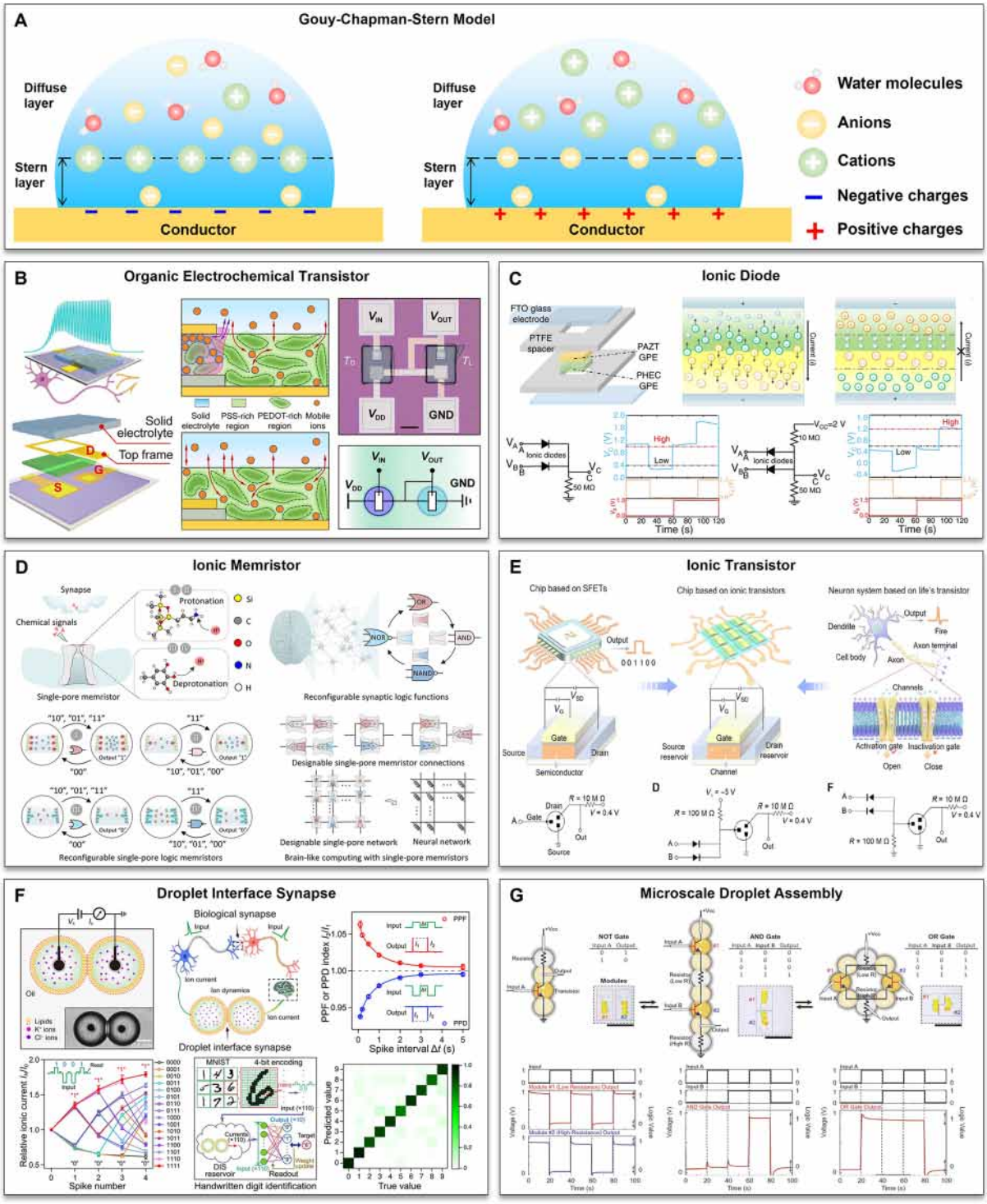

Figure 3. Iontronic logic enabled by dynamic regulation of EDLs at conductive interfaces. (A) GCS EDL model; (B) Organic electrochemical transistor. This figure is quoted with permission from the authors[36]; (C) Ionic diode. This figure is quoted with permission from the authors[37]; (D) Ionic memristor could realize OR, AND, NOR, and NAND logic gates. This figure is quoted with permission from the American Chemical Society[39]; (E) Ionic transistor. This figure is quoted with permission from American Chemical Society[40]; (F) Droplet interface synapse. This figure is quoted with permission from the American Association for the Advancement of Science[41]; (G) Microscale droplet assembly could realize NOT, AND, and OR logic gates. This figure is quoted with permission from The American Association for the Advancement of Science[42]. EDLs: Electrical double layers; EDL: electrical double layer; GCS: Gouy-Chapman-Stern; NOR: NOT OR gate; NAND: NOT AND gate; PSS: poly(styrenesulfonate); PEDOT: poly(3,4-ethylenedioxythiophene;

GND: ground; SFETs: solid-state field-effect transistors; AI: artificial intelligence; PPF: paired-pulse facilitation; PPD: paired-pulse depression; MNIST: Modified National Institute of Standards and Technology database; DIS: droplet interface synapse.

the surface charge within sub-10 nm carbon nanopores under low applied bias, these devices exhibit ambipolar operation, a current on/off ratio exceeding 10^4, and dual-mode switching between p- and n-type conduction. Arrays of such transistors have been configured into NOT, NAND, and NOR logic gates, operating stably at voltages near 1 V and demonstrating low-energy, high-density iontronic computation. Extending the concept to soft, bioinspired systems, droplet-interface synapses form lipid bilayers between aqueous droplets[41] [Figure 3F]. Voltage stimulation induces charge redistribution and transient pore formation in the bilayer, producing coupled memristive and memcapacitive responses that realize spike-rate-dependent plasticity, Hebbian learning, and even reservoir computing for pattern recognition tasks. Building on this droplet-interface paradigm, "dropletronic" hydrogel circuits replace purely aqueous droplets with nanoliter-scale silk-protein hydrogel droplets that self-assemble into mechanically robust iontronic junctions[42] [Figure 3G]. In this architecture, cation- and anion-selective hydrogel microdroplets form diode- and transistor-like elements with millisecond response times and microwatt power consumption. Modular assembly of these droplets enables reconfigurable logic gates and synaptic behaviors such as long-term plasticity, while maintaining excellent biocompatibility for direct coupling to cardiac cell sheets. Together, these results establish a clear design principle: applying an electric field to a conductive interface enables precise, reversible reconfiguration of the EDL, which in turn governs ionic migration and interfacial conductivity. Because the active region is confined to the nanoconfined EDL, only a minute quantity of charge needs to move, offering intrinsically low switching energy. The approach is also highly adaptable: device characteristics can be tuned by electrode material, surface chemistry, and electrolyte composition, while soft or bio-derived interfaces permit seamless integration with living tissues and aqueous environments. Compared with gradient- or mechanically driven iontronics, EDL-gated systems provide direct electronic addressability, higher integration density, and dynamic reprogrammability, positioning them as a cornerstone for next-generation iontronic logic, neuromorphic processors, and bio-interfaced computing platforms.

Iontronic logic driven by dynamic regulation of EDLs at dielectric interfaces

Research on conductor-liquid interfaces has demonstrated that externally applied potentials can dynamically reorganize EDLs, enabling diverse logic operations. By contrast, dielectric-liquid interfaces, which are prevalent in both natural and engineered systems, remain far less understood. Because dielectric materials are electrically insulating, interfacial charge formation cannot be directly modulated by an applied voltage. The two-step EDL model proposed by Wang *et al.* offers a conceptual framework for describing charge accumulation at these insulating interfaces[43] [Figure 4A], but it is primarily applicable under thermodynamically stable or quasi-static conditions. In practical operational environments, dielectric-liquid interfaces are frequently subjected to mechanical contacts, vibrations, and spontaneous electrostatic perturbations, inducing nonequilibrium charge redistribution and time-dependent electrostatic asymmetries that the conventional model cannot account for. To address these dynamic phenomena, Wei *et al.* proposed the triboiontronics EDL model in 2023[43] [Figure 4B], which incorporates contact-electrification-induced polarization as an active mechanism for modulating interfacial charge. This model can be regarded as an extended manifestation of triboelectric-induced polarization control, in which interfacial polarization dynamically governs ion distribution and potential modulation within the EDL. In this framework, triboelectric charges generated by mechanical contact create localized electrostatic fields that continuously reconfigure both the Stern and diffuse layers in real time, without any external voltage. The framework defines two complementary polarization states. Under forward polarization, a positively charged dielectric approaching the solid-liquid interface repels cations from the immediate surface while

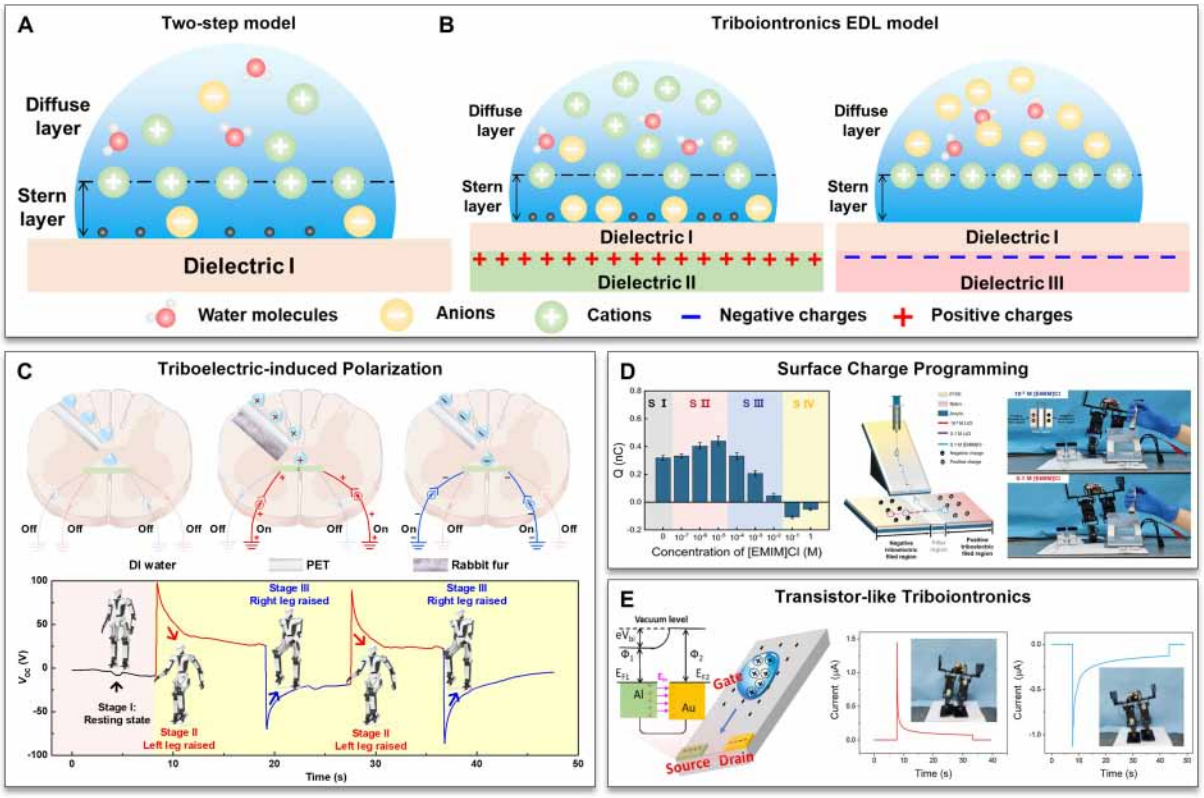

Figure 4. Iontronic logic driven by dynamic regulation of EDLs at dielectric interfaces. (A) Two-step EDL model; (B) Triboiontronics EDL model; (C) Triboelectric-induced polarization. This figure is quoted with permission from Elsevier Inc.[43]; (D) Surface charge programming. This figure is quoted with permission from Wiley-VCH GmbH[48]; (E) Transistor-like triboiontronics. This figure is quoted with permission from Elsevier Inc.[49]. EDLs: Electrical double layers; EDL: electrical double layer; DI: de-ionized water; PET: polyethylene terephthalate; PTFE: polytetrafluoroethylene; [EMIM]Cl: 1-ethyl-3-methylimidazolium chloride.

attracting low-hydration-energy anions, which adsorb extensively onto the solid, forming a strongly negative Stern layer accompanied by a cation-rich diffuse layer that balances the interfacial charge. Under reverse polarization, a negatively charged dielectric draws cations and repels anions. Because hydrated cations possess high solvation energy and are less likely to dehydrate, they accumulate primarily near the outer Helmholtz plane, while the inner plane is dominated by oriented water dipoles, giving rise to a net positive potential across the Stern layer. This reversible inversion of interfacial polarity establishes a bistable EDL architecture, enabling programmable, mechanical control of surface charge profiles without the need for conductive substrates or continuous power input. In contrast to conventional triboelectric nanogenerators (TENGs)[44-46], which primarily function as passive energy harvesters converting mechanical motion into transient electrical outputs, triboiontronic logic emphasizes active and programmable regulation of EDL states. While TENGs exploit charge transfer for power generation, the triboiontronic framework leverages triboelectric-induced polarization to dynamically encode, store, and switch interfacial charge configurations, thereby realizing logic-state modulation and information processing rather than energy output. This distinction highlights that triboiontronic systems transform the triboelectric effect from an energy-conversion mechanism into an information-control paradigm, bridging electromechanics and iontronics through dynamically tunable interfacial polarization. This advance was highlighted in a peer commentary[47], which noted that the triboiontronics model offers both a unified explanation for nonequilibrium interfacial charge dynamics and a versatile platform for energy harvesting and neuromorphic iontronic logic. The authors emphasized that integrating contact electrification with dynamic

EDL modulation constitutes a conceptual breakthrough, providing a novel *in situ* probe of interfacial physics and paving the way for soft, self-powered information-processing systems.

Building directly on this mechanism, a bioinspired neuromorphic circuit was demonstrated in which bidirectional triboelectric-induced polarization, generated through solid-solid contact electrification, regulated the charge distribution within the sub-nanometer Stern layer, thereby switching the ionic polarity of the diffuse layer[43] [Figure 4C]. Physical contact states functioned as logic inputs, with the polarity of the resulting ionic current defining the output. By employing a fine water mist as the charge carrier, the system generated direction-specific ionic currents capable of toggling light-emitting diodes and actuating a virtual robotic interface, effectively emulating bidirectional neuronal control of limb movement, all without external electrical bias. The polarity switching was fully reversible and non-interfering, ensuring high fidelity and operational robustness. Subsequent studies have further extended the logic-control capabilities of dielectric-interface triboiontronics[48]. A triboelectric-wetting droplet platform combined solid-liquid and solid-solid contact electrification to propel charged droplets at speeds up to 450 mm/s, including uphill motion [Figure 4D]. By programming surface charge distributions, droplets of opposite polarity were guided along predefined pathways to selectively open or close circuits, enabling Boolean operations and timing-dependent, cascaded logic. Controlled droplet merging or splitting triggered chemical logic outputs, where color changes or pH variations directly represented digital signals, all without continuous electrical input. In parallel, a transistor-like triboiontronic architecture was developed, in which a triboelectrically charged water droplet served as a movable gate sliding between aluminum (Al) and gold (Au) electrodes with differing work functions[49] [Figure 4E]. The built-in potential generated a stable ionic current of 4.6 mA at 0.6 V, achieving a record charge density of 13.9 mC/m^2, while adjusting droplet position or volume produced discrete high/low current states, enabling both logic control and simple neuromorphic functions such as threshold sensing and pulse-rate-dependent plasticity. Collectively, these advances establish a self-powered, mechanically programmable paradigm in which contact-induced polarization dynamically reconfigures the dielectric-liquid EDL, encoding input states as tunable ionic polarity and direction-specific electronic outputs. By eliminating the need for externally applied voltage and operating effectively in aqueous and biological environments, dynamic EDL regulation at dielectric interfaces offers a foundational strategy for next-generation iontronic logic devices, encompassing multi-gate Boolean computation, chemical logic, and neuromorphic information processing, with applications ranging from soft robotics to adaptive brain-machine interfaces.

To elucidate the distinct operational characteristics of different iontronic logic control mechanisms, the representative modes are summarized in Table 2. Each mode is defined by its characteristic input, driving principle, output, and energy scale. Ion-concentration-gradient-driven logic relies on asymmetric ion distributions to generate electrochemical potential differences for information encoding. Mechano-driven logic converts mechanical deformation into ionic transport and polarization, enabling direct mechano-responsive signal outputs. Iontronic logic driven by the dynamic regulation of EDLs at conductive interfaces employs external bias to modulate ionic-electronic coupling and interfacial charge dynamics with high precision. In contrast, iontronic logic driven by the dynamic regulation of EDLs at dielectric interfaces harnesses triboelectric-induced polarization as an internal driving field to achieve self-powered, real-time control of ionic and interfacial states. Collectively, these four logic control modes illustrate complementary strategies for coupling ionic transport, interfacial polarization, and energy conversion, forming the physical foundation of iontronic logic systems.

CONCLUSION AND OUTLOOK

Iontronic logic control, spanning strategies from ion-concentration-gradient-driven and mechanically

Table 2. Comparative summary of iontronic logic control mechanisms

Logic control mode	Input	Driving principle	Output	Energy scale/ operation characteristics
Ion-concentration-gradient-driven logic	Ion concentration gradient	Ionic diffusion	Ionic voltage/current output driven by the ion-concentration gradient	Self-powered
Mechano-driven logic	Mechanical pressure	Mechano-ionic coupling via piezoionic polarization	Pressure-dependent voltage/current	Self-powered
EDL regulation at conductive interfaces	External bias or redox potential	Ionic-electronic interaction at the solid-liquid interface	Interfacial potential/current	Several volt levels, externally powered
EDL regulation at dielectric interfaces	Contact electrification/ asymmetric EDLs	Triboelectric-induced polarization regulating EDL	Self-generated current/ionic redistribution	Self-powered

EDLs: Electrical double layers; EDL: electrical double layer.

induced transport to the dynamic regulation of EDLs, is rapidly emerging as a versatile platform for next-generation information technologies [Figure 5]. This field is poised to evolve toward an integrated information platform, where iontronic circuits act as intelligent interfaces that bridge sensing, computation, and actuation within a single matter-based system. Such platforms will couple ionic communication with electronic or photonic subsystems to realize adaptive, energy-autonomous devices capable of processing multimodal environmental data in real time[50]. Neural interfaces represent another compelling frontier, as iontronic devices, operating with ionic carriers and aqueous electrolytes, naturally align with the signaling chemistry of the nervous system, enabling stable, low-impedance coupling for brain-machine communication and closed-loop neuroprosthetics[51]. In neuromorphic systems, the intrinsic analog tunability and memory plasticity of dynamically reconfigurable EDLs provide a physical substrate for synapse-like behaviors, paired-pulse facilitation, spike-rate-dependent plasticity, and learning rules, offering a low-power pathway toward spiking neural networks and adaptive computing[52]. Iontronic architectures are also highly suitable for artificial sensing, where direct transduction of mechanical, chemical, or thermal stimuli into ionic signals can yield large-area, self-powered tactile skins or gustatory and olfactory mimics with high spatial and temporal resolution[53]. Moreover, the ability to generate localized ionic microenvironments and controllable electric fields on demand opens opportunities for microscale therapies, including site-specific drug delivery, wound-healing stimulation, and electrochemical disinfection, where soft, biocompatible, and wireless operation is essential[54]. Together, these prospects outline a coherent roadmap from fundamental ion-matter coupling toward intelligent, embodied, and sustainable iontronic logic systems. Beyond the conceptual and mechanistic advances, practical integration represents an essential step toward realizing the technological potential of iontronic logic. Owing to their soft, deformable nature and aqueous operation, iontronic devices can be seamlessly combined with flexible and stretchable electronic platforms, enabling the creation of hybrid neuromorphic and bio-interfaced systems. In such architectures, iontronic elements can serve as interfacial processors that mediate signal transduction between biological tissues and conventional electronic circuits, maintaining ionic–electronic continuity while reducing impedance mismatch. Coupling iontronic logic with flexible electronics thus opens pathways for energy-autonomous artificial synapses, conformal neural interfaces, and adaptive sensory skins capable of localized computation and distributed learning. The convergence of these technologies will be critical for advancing embodied and bio-integrated intelligence, marking a tangible step from fundamental ion-matter coupling toward scalable, real-world applications.

Although iontronic logic control has demonstrated substantial potential, several critical challenges must be addressed to enable its broad adoption and practical deployment. Device response speed and operational bandwidth remain key constraints, as ionic diffusion and interfacial polarization typically limit switching to millisecond or slower timescales, significantly lower than those achievable in conventional semiconductor

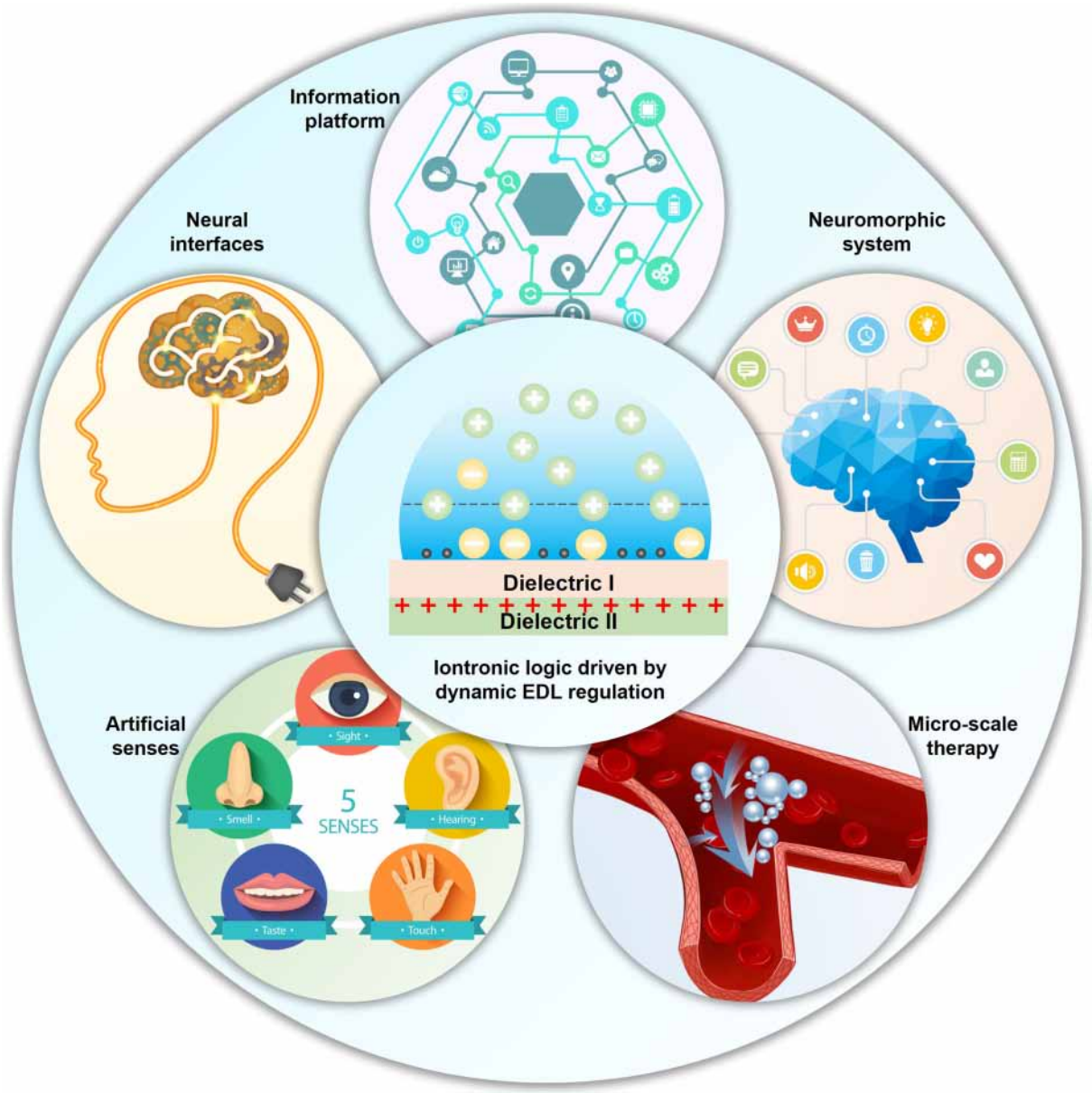

Figure 5. Potential development directions in the field of iontronic logic control. Graphical elements in this figure were sourced from the licensed design platform 51yuansu (https://www.51yuansu.com/) and assembled by the authors using Microsoft PowerPoint. All graphical materials are used under purchased copyright licenses. EDL: Electrical double layer.

circuits. Long-term stability and environmental robustness also require careful consideration, since interfacial charge distributions and ionic conductance can be sensitive to fluctuations in parameters such as humidity, temperature, surface chemistry, etc. Addressing these issues necessitates the development of durable materials, advanced encapsulation strategies, and mechanisms to maintain consistent interfacial charge profiles over extended periods. In addition, scalable integration and the realization of complex circuit architectures remain formidable challenges: while individual iontronic devices already exhibit a wide range of logic functionalities, constructing dense, addressable arrays with reproducible performance and seamless compatibility with existing microelectronic or microfluidic platforms will require innovations in fabrication, interconnect design, and system-level engineering. Overcoming these limitations is essential to

transition iontronic logic control from laboratory-scale demonstrations to a robust, versatile platform capable of supporting neuromorphic computing, soft robotics, adaptive biomedical electronics, and a broad spectrum of next-generation, energy-autonomous information-processing applications.

In summary, iontronic logic control has emerged as a transformative paradigm for information processing, surpassing some of the inherent limitations of conventional semiconductor electronics. By employing ions as dynamic charge carriers and leveraging mechanisms such as ion-concentration gradients, mechanical stimuli, electric or triboelectric field regulation on EDLs, researchers have shown that logic operations can be implemented entirely through ionic phenomena, frequently operating without the need for sustained external power[24,25]. These developments underscore the unique capability of iontronic systems to integrate energy harvesting with signal processing, operate seamlessly in soft and aqueous environments, and interface directly with biological systems. As highlighted in this Perspective, the field is now poised to advance from proof-of-concept demonstrations to fully integrated platforms supporting neuromorphic computing, adaptive sensing, and bio-interfaced electronics. Achieving this transition will require improvements in switching speed, long-term stability, and scalable integration, alongside deeper insights into nonequilibrium ionic-electronic coupling at complex interfaces. Addressing these challenges will enable iontronic logic control to evolve from a compelling laboratory concept into a mature, versatile technology for next-generation computing, soft robotics, biomedical devices, and other energy-efficient data-intensive applications.

DECLARATIONS

Authors' contributions

Conceptualized the idea and led the project: Wei, D.; Wang, Z. L.
Made substantial contributions to writing the paper: Wei, D.; Li, X.

Availability of data and materials

Not applicable.

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Conflicts of interest

Wei, D. is Editor-in-Chief of the journal *Iontronics*. Wang, Z. L. is Honorary Editor-in-Chief of the journal. Wei, D. and Wang, Z. L. were not involved in any steps of the editorial process, notably including reviewers' selection, manuscript handling or decision making. Li, X. declares that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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