Iontronics

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# Neural signal processing in an ionic gel

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Ions in a multiphasic gel can exhibit complex cross-interface dynamics that can be used for neuromorphic processing.

Biological systems use multiple ion species in parallel to communicate, process and store information. Inspired by this, the field of biointronics aims to create artificial systems that can interface with biological systems through ions and biological molecules[1], and with the help of biomimetic or bioinspired designs[2]. A range of biointronic devices have already been developed, including biphasic gel devices with an internal structure similar to that of water-in-oil emulsions[3]. In the biphasic gel, ions experience hydration–dehydration cycles when hopping between the aqueous droplets under electric fields (Fig. 1a). This process enlarges the discrepancy in transfer energy among ion species and leads to the separation of different ions, which is useful for ion-selective biological modulation. Writing in *Nature Electronics*, Ziguang Zhao and colleagues now report an ion transporter that is based on a multiphasic gel and can be used for ionic neuromorphic processing[4].

The ion transporter has a Janus structure composed of two biphasic gels that intersect in the middle (Fig. 1b). The two gels are identical in structure but differ in composition: one contains ion-enriched polyanionic electrolytes, and the other contains polycationic electrolytes. This allows the ion transport behaviour of the biphasic gels to be preserved while introducing new capabilities during electrical scans. Conventional iontronic diodes operate by being ionic conductive in one

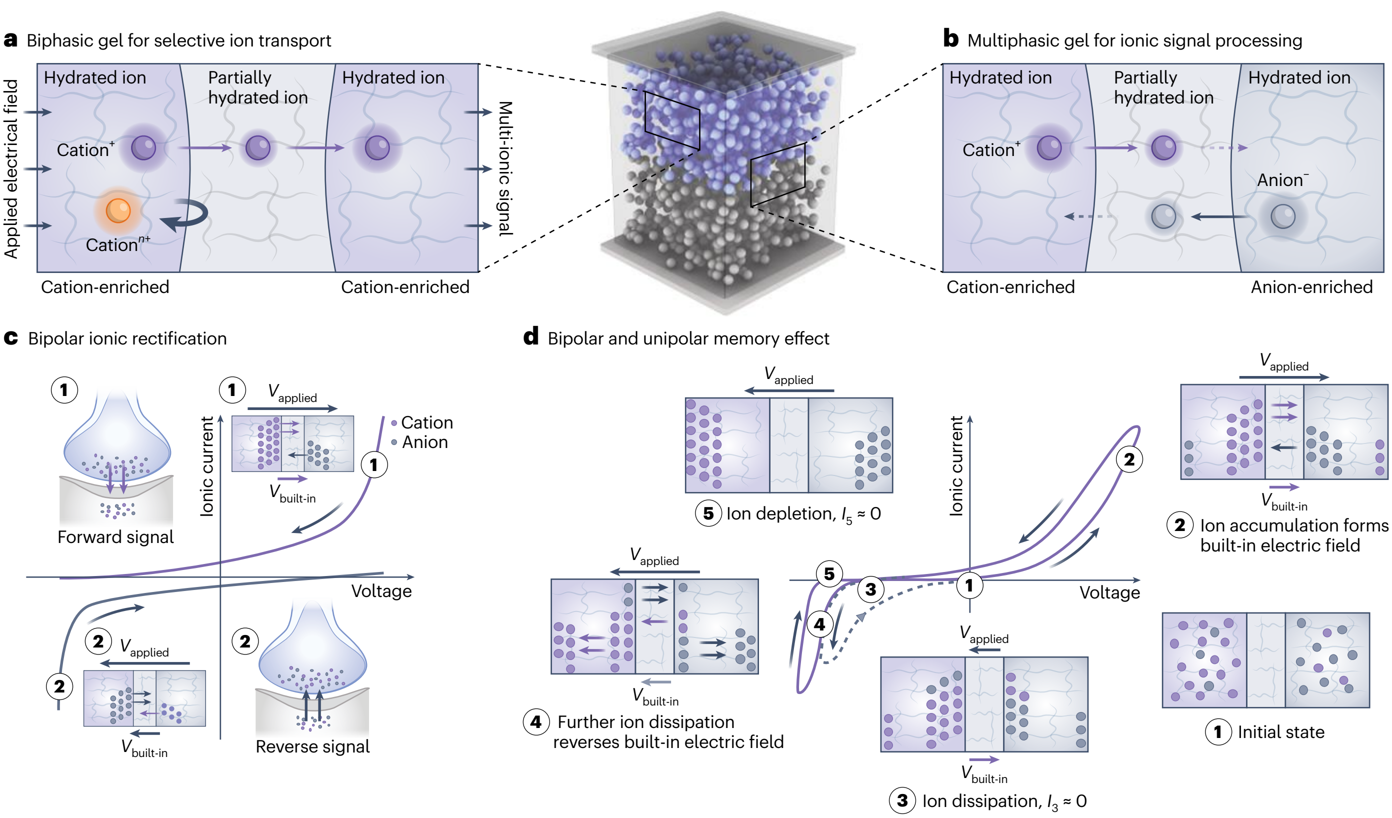


**Fig. 1 | Ion transporters based on multiphasic gels. a**,**b**, Selective ion transport in a biphasic gel (**a**) and ionic signal processing in a multiphasic gel (**b**). The multiphasic gel structure of the ion transporter has a cation-enriched (purple) and an anion-enriched (grey) phase. **c**, The bipolar rectification of the transporter mimics bidirectional synaptic communication and is governed by the interplay of the applied voltage ($V_{applied}$) and built-in voltage ($V_{built\text{-}in}$). **d**, Memory effect of the ion transporter. The purple curve shows a crossed loop, which is a characteristic of bipolar memory. As the voltage is swept from positive to negative, ions first accumulate at the intersection (step 1 to 2) and then gradually dissipate as the input voltage reverses (step 2 to 3). The $V_{applied}$ counteracts the preformed $V_{built\text{-}in}$, resulting in zero ionic current at step 3 ($I_3$). The accumulated ions continue to dissipate along the applied electric field, resulting in a reversed ionic current (step 3 to 4). Ion depletion at the intersection forms a low-conductive state (step 4 to 5), resulting in zero ionic current at step 5 ($I_5$), and bipolar memory behaviour occurs (step 5 to 1). The grey dashed line shows the characteristic of unipolar memory with a non-crossing current–voltage curve (step 4 to 1). Figure adapted from ref. 4, Springer Nature Limited.

direction, known as unipolar rectification[5]. By contrast, the transporter exhibits a bipolar rectification effect, similar to the bidirectional signal transmission at a synaptic interface (Fig. 1c).

This bipolar rectification can be understood by considering the cation and anion accumulation at the gel intersection. When sweeping the input voltage from positive to negative (linear sweep voltammetry), cations first accumulate at the boundaries of the cation-enriched phase, and anions mirror that in the anion-enriched phase. Therefore, a built-in electric field forms, enhancing cross-interface ionic conductivity and leading to a high ionic current. Following the voltage scan, the built-in electric field gradually dissipates, leading to a decreasing current and ionic rectification. In the reverse process, the remaining anions (less than the dominant cations) in the cation-enriched phase and the remaining cations in the anion-enriched phase undergo the same accumulation and dissipation processes at the boundaries, forming a reversed ionic rectification effect.

The bipolar rectification can be further amplified by using different ion species. For example, multivalent ions, such as calcium and aluminium ions, exhibit slow interfacial transport in the biphasic gels, thereby enhancing the ion accumulation and the rectification ratio. The ion transporter can, in particular, be configured for ion-specific rectification across 16 ion species, highlighting the multistate ionic signal processing capability of the system.

The researchers — who are based at University of Chinese Academy of Sciences in Beijing, Hangzhou Institute of Medicine, Capital Medical University in Beijing, and Tsinghua University — also show that the transporter can exhibit bipolar memory behaviour. This involves a self-crossing current–voltage curve and two ionic conductive states when different voltage polarities are applied[6,7] (Fig. 1d). During cyclic voltammetry, ions initially accumulate at the intersection as the voltage increases and then gradually dissipate as the input voltage reverses. As in the rectification process, a built-in electric field is generated, thereby enhancing the ionic current. (A positive current also exists when the voltage vanishes, which is the result of the remaining accumulated ions and the built-in electric field.)

As the input voltage decreases further, there is a moment when the applied voltage counteracts the preformed built-in electric field, resulting in zero ionic current. In the next instant, the accumulated ions continue to dissipate along the applied electric field, resulting in a reversed ionic current. Ions can cross the intersection under the combined influence of the applied and built-in electric fields. The scanning voltage and duration determine the degree of ion dissipation, which can eventually lead to ion depletion at the intersection, forming a low-conductive state and bipolar memory behaviour. By comparison, when electrical inputs are insufficient to dissipate the built-in electric field, the transporter exhibits unipolar memory behaviour, with a non-crossing current–voltage curve.

The memory behaviour of the device can be modulated with different ion species. For example, a transporter with calcium and aluminium ions shows memory enhancement under pulsed voltages, whereas those with chloride and hypochlorite ions show memory depression. Moreover, multiple ion transporters can be connected in parallel to achieve selective memory enhancement or depression.

The team also shows that the transporter can be interfaced with biological neurons to enable dynamic transmission of neuronal signals. In particular, the devices are interfaced with the transected sciatic nerve of a rat. Original neural signals from the proximal sciatic nerve can pass through the ion transporters and generate postsynaptic ionic currents at around 2 Hz during tail-pinch stimulations. The energy consumption of the ion transporter is 0.61 pJ per nerve activity, similar to the low power consumption of biological neurons[8].

A number of challenges remain to be addressed with the system. The ion transporter has a low response speed due to slow ion accumulation and dissipation. Device miniaturization might provide a solution, which could mitigate ion hysteresis and the associated system response speed[9]. At the same time, device integration is also important for scaling up the ion transporter into a neuromorphic system. Moreover, only a limited number of ion species are available for certain functions. Alternative approaches could be explored to regulate multi-ion dynamics, such as with light, heat and mechanical stimuli, mimicking biological sensing, signal processing and feedback behaviours[10].

For future biointerface applications, the system may also need to process a broad range of biomolecules, including neurotransmitters, metabolites and therapeutic factors. These systems will, in addition, need to be soft, biocompatible, small and reliable for in vivo operation. With such advances, bioiontronic interfaces could be developed for use in sensory repair, reconstruction and even augmentation.

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### Competing interests

The authors declare no competing interests.