Fluidic memristor: Bringing chemistry to neuromorphic devices

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Neuromorphic devices, devices with resistance switch dynamic emulating the behavior of neurons, are experiencing a surge in development due to the demand for artificial intelligence and therapeutic devices such as neuroprosthetics.[1] Toward reproducing the behaviors of neurons with artificial devices, neuromorphic devices based on two-terminal memristors (devices with a single-valued relationship between charge Q and magnetic flux φ, i.e., $d\varphi = MdQ$) with various mechanisms (e.g., redox, phase change, magnetic tunnelling, and ferroelectricity) have been developed for various applications, like in-memory computing or intelligent sensing.[2] However, the performances and functions of these devices still lag behind those of real neurons. For example, biological neurons are strongly responsible for chemical changes in electrolyte solutions induced by transmitters and regulators, while most neuromorphic devices only show responses to the stimulations of electrical signals. Detecting and responding to these chemical signals could not only improve the performances of neuromorphic computing but also offer brand-new functions in brain-computer interfaces. However, the fabrication of neuromorphic devices responsible for chemical information remains a great problem since the founding of the memristor.

Recently, fluidic memristors have been developed that use ions in electrolyte solutions as carriers, bringing new opportunities for the development of neuromorphic devices that are responsible for chemical signals. Inspired by the behaviors of neurons that realized neuroplasticity by controlling the behaviors of ion channels, our group has designed a polyelectrolyte-confined fluidic memristor (PFM)[3] in which neuromorphic functions are accomplished with PFMs by controlling the confined ion transport with polyelectrolyte-ion interactions. Through this intensive interaction in spatial confinement, chemical responses of PFMs could be achieved by regulating interactions between ions and polyelectrolytes using different ion species or ionic strength, and neuroplastic functions could be regulated with chemical changes and even the use of real neurotransmitter ATP. Moreover, with this chemical-regulated neuroplasticity, PFMs are capable of emulating the chemical-electrical signal transduction of neurons, offering opportunities to transform chemical stimulation changes into electrical information in a neuromorphic encoding dynamic. Meanwhile, Bocquet et al. achieved neuroplasticity with ions in ultraconfined 2D nanochannels.[4] With intensive ion-surface interactions in subnanoscale spatial confinement, nonvolatile ionic memory was achieved, which contributed to the realization of Hebbian learning emulation. These fluidic memristors showed that neuromorphic functions can be emulated with ions in electrolyte solutions.

Different from solid memristors where electrons or ions of one specific species are the major carriers, fluidic memristors utilize ions in the electrolyte solution, bringing new opportunities for the development of neuromorphic devices. Firstly, a wide range of ion species could coexist and move freely in electrolyte solutions such as cerebrospinal fluid. These coexisting ions contributed to abundant chemical information in ion currents compared with solid memristors. This colorful chemical information offered the possibility of producing highly parallel computing devices with ions in electrolytes. Secondly, ions possess versatile chemical characteristics, which means the possibility of controlling their behaviors with specific chemical interactions emulating the ligand-gated ion channels in neurons. With these chemical regulation strategies, electrical signals as well as chemical signals could participate in the signal processing of fluidic memristors, providing brand-new chances to the research field of memristors. More importantly, ions are not only major charge carriers of fluidic memristors but also charge carriers of biological systems. Therefore, the biological compatibility of fluidic memristors offers unparallel convenience for the communication between devices and real neurons. These unique characteristics of ions contributed to not only promising possibility of improving the performances of neuromorphic devices but also chances of raising their biocompatibility with fluidic memristors.

Based on these unique characteristics, fluidic memristors offered completely new inspiration for chemists, as chemistry is bringing new opportunities to the design of neuromorphic devices. Firstly, chemical design is always a powerful tool for creating spatial confinement. The application of porous materials such as MOFs, 2D materials, and hydrogels would bring new functionalities for fluidic memristors. The subnanoscale confinements in these materials are even comparable to the size of biological ion channels, allowing the observation of counterintuitive ion transport behaviors like ultrafast ion transport. These effects indicated the potential of producing nanofluidic devices with performances beyond that of solid memristors. Furthermore, by introducing precise chemical modification to the spatial confinement, more functionalities could be added to fluidic memristors. For example, with specific recognition units like aptamers or antibodies, recognition of real neurotransmitters might be achieved with fluidic memristors as was achieved by ligand-gated ion channels. Hence, with rational control of the chemical interaction between ions and the surface, reading and processing of ion current information induced by specific species would be possible, and far more information could be unveiled from the ion currents in fluidic memristors. This opens possibilities for achieving more complex neuromorphic functions by tuning these chemical interactions. With molecular interactions as powerful tools, not only new memristors with outstanding performance could be fabricated, but also new functions could be developed by leveraging these effects.

On the other hand, these fluidic memristors also produced new ways of controlling neuromorphic devices with chemicals. Firstly, by controlling the multiplex ion species in fluidic memristors, neural behaviors of high complexity could be simulated with minimal circuit complexity. For example, the complex Hodgkin-Huxley model of neurons could be achieved with simply two parallel fluidic memristors mimicking the K^+ channel and Na^+ channel respectively. Hence, chemical-interaction-based fluidic memristors allow driving memristors with low operation voltage and less energy consumption. In this case, these fluidic memristors offered the opportunity of establishing brain-mimicking computing platforms with energy efficiency by emulating neural behaviors. More importantly, by controlling fluidic memristors with chemical interactions, not only electrical signals (ion current) but also chemical information (neurotransmitters) that participate in the signal processing of neurons could be detected and processed with fluidic memristors. These devices could serve as powerful platforms for the connection between hardware and neurons with not only electrical communication but also chemical communication.[5] By using chemical interactions to regulate the behaviors of fluidic memristors, not only complex neuromorphic functions could be achieved with less circuit complexity and low energy consumption, but also chemical information could be recorded and processed.

Collectively, with chemical interaction in spatial confinement, fluidic memristors with ions in electrolytes for charge carriers could be fabricated by tuning the behaviors of ions with chemical interactions in confined electrolytes. Different from electrons in solid memristors, ions in these fluidic memristors behave with a series of unique characteristics, which offer enormous potential in serving as charge carriers with colorful functionalities. The rise of these fluidic memristors provides not only new opportunities that bring new chemistries in the design of neuromorphic devices but also the possibility of regulating the behaviors of neuromorphic devices with chemical information changes in these neuromorphic systems (Figure 1). However these newborn devices still face a wide range of challenges needing to be addressed. For example, the exploitation of new functions of fluidic memristors remains a long-term challenge that relies on the

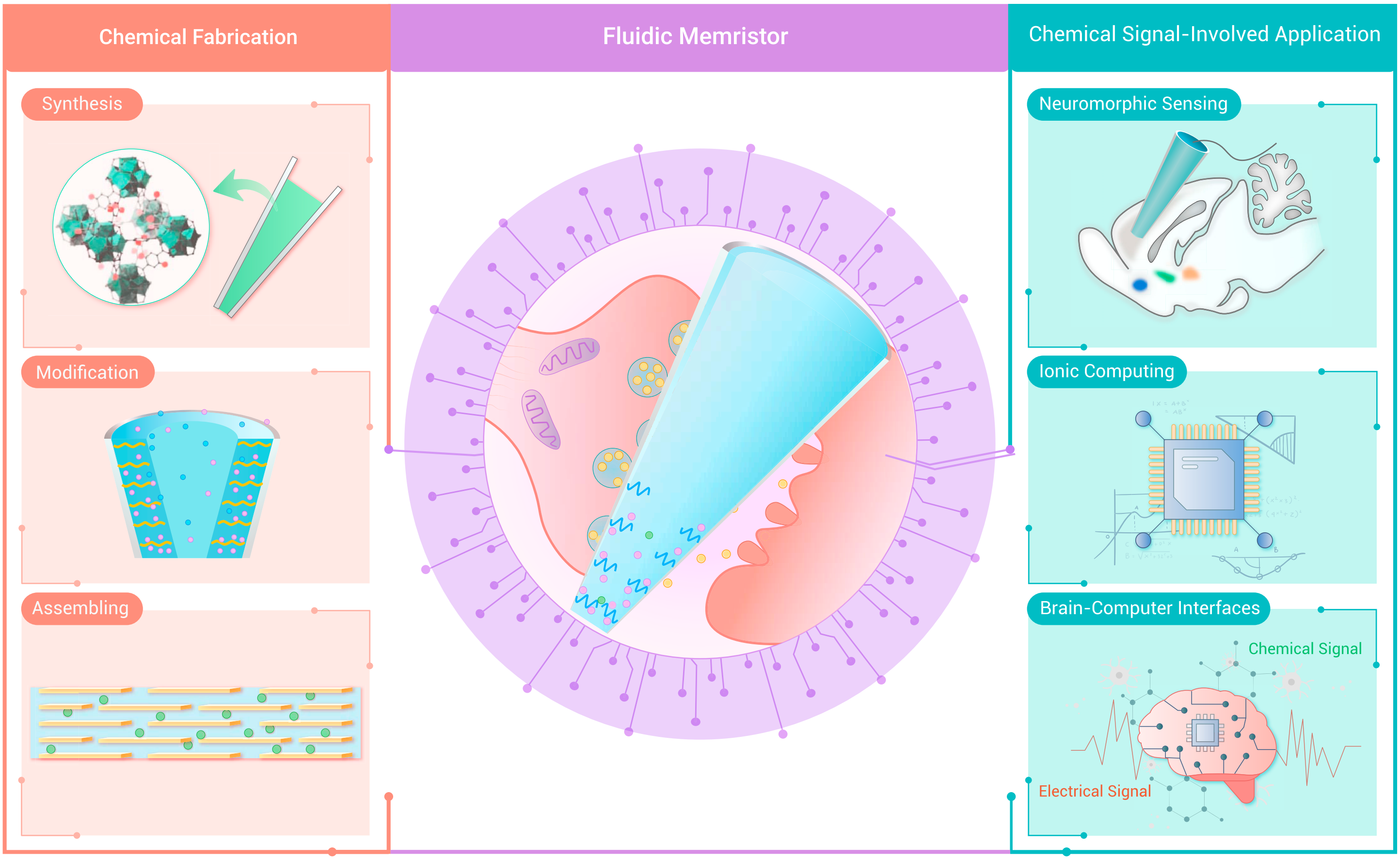

Figure 1. Chemical fabrication and chemical signal-involved application of fluidic memristors.

control of the interaction kinetics in fluidic memristors with rational chemical design. The rational control of reversibility as well as the selectivity of chemical interactions in fluidic memristors would contribute to neuromorphic functions of more complexity. Additionally, the stability, on/off ratio, and the large-scale integration of these fluidic memristors are still unsolved problems that require the development of new chemistries as well as electronic strategies. In short, the development of these fluidic memristors paved a new way for introducing chemical design into the research field of neuromorphic devices. The advancement of these fluidic-based devices offers a promising future for brain-mimicking computing as well as brain-computer interfaces and relies on multidisciplinary efforts from not only electronics and physics but also chemistry and material science.

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DECLARATION OF INTERESTS

The authors declare no competing interests.