Magneto-ionics for low-power memory and neuromorphic applications

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Voltage control of magnetism offers significant potential for enhancing energy efficiency in nanoscale devices. By utilizing electric fields instead of magnetic fields or electric currents, the detrimental effects of Joule heating and energy dissipation can be minimized. In recent times, we have demonstrated the ability to induce reversible and non-volatile alterations in the magnetic properties (such as coercivity and magnetic moment) of nanoporous films. These films consist of metal alloys (such as CuNi and FeCu) or oxides (like FeO_x and $CoFe_2O_4$). This manipulation is achieved by applying an electric field via a liquid electrolyte gate, even at room temperature [1,2]. Furthermore, significant progress has been made in the field of magneto-ionics, which involves voltage-driven ion transport in magnetic materials. Traditionally, this process relied on the controlled migration of oxygen or lithium ions. However, we have now demonstrated that the transport of nitrogen ions can also be triggered at room temperature in films composed of transition metal nitrides (such as CoN, FeN, and CoFeN) through liquid electrolyte gating [3,4]. Nitrogen magneto-ionics allows for reversible ON-OFF transitions of ferromagnetic states at faster rates and lower threshold voltages compared to oxygen magneto-ionics. This advantage arises from the lower activation energy required for ion diffusion and the lower electronegativity of nitrogen when interacting with cobalt, as compared to oxygen. Notably, nitrogen transport occurs uniformly through a plane-wave-like migration front, without the need for diffusion channels, which is particularly intriguing for the implementation of multi-stack memory devices. Moreover, both oxygen and nitrogen magneto-ionics can be utilized to replicate essential neuromorphic and synaptic functionalities, such as spike amplitude-dependent plasticity, spike duration-dependent plasticity, and long-term potentiation/depression. By employing DC and pulsed voltage actuation at frequencies ranging from 1 to 100 Hz, we can simulate learning, memory retention, forgetting, and self-learning through maturity (post-stimulated learning). This novel approach enables the device to decide between self-learning and forgetting emulation, as desired, following a voltage input. Consequently, this presents a ground-breaking method to emulate specific neural functionalities, including learning during deep sleep, which is challenging to achieve using other materials currently employed in neuromorphic computing applications.

References

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