2D Material-Based Electronic Synapses Learn Like Brain

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Highly-scalable metal-insulator-metal based electronic synapses fabricated using resistive-switching multilayer hexagonal boron nitride (h-BN) sheets can reliably emulate both long term plasticity and short term plasticity, simultaneously, with an ultra-low standby power consumption of 1fW.

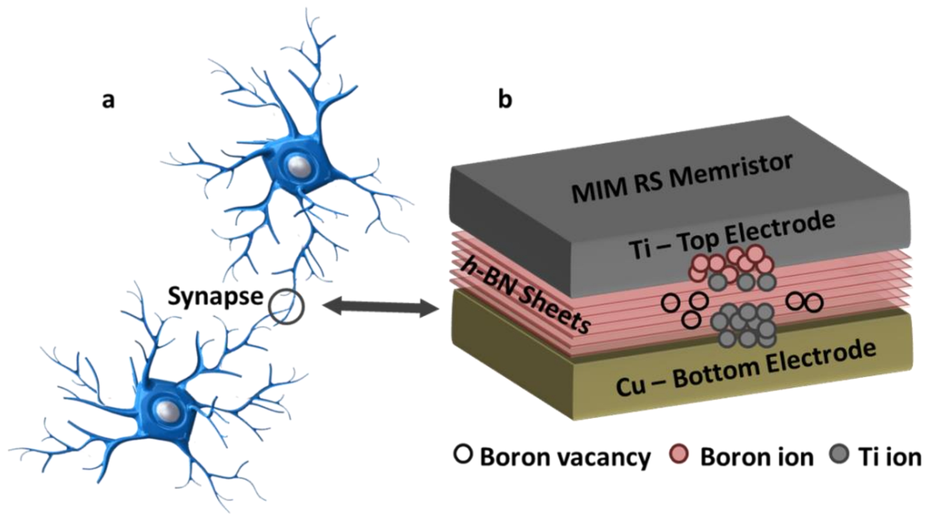
Neuromorphic computing is considered as a promising technology for implementing brain-inspired applications such as speech, self-learning and recognition of patterns using energy efficient spiking networks [1]. In the neural system, neurons are interconnected via synapses that enable the flow of electrical and chemical signals. These neural connections are either strengthened or weakened in response to increases or decreases in their activity via a biologically-observed process called Spike-Timing-Dependent-Plasticity (STDP). The change in the weight of the synapses, also called synaptic plasticity, explains how the brain learns and memorizes. Short term synaptic plasticity (STP) lasts for minutes where the synaptic connection is temporarily enhanced then goes back to its initial state, while long term plasticity (LTP) is the prevailing model for how the brain stores information and it lasts from minutes to hours and days. LTP can also be achieved via repeated stimulations that cause a perpetual change in the connection. Therefore, the capability to imitate the synaptic functions, especially LTP and STP behaviors, is at the core of neuromorphic computing [2].

Recent studies have shown that LTP and STP functions can be imitated using resistive-switching (RS) electronic devices which consist of a compact metal/insulator/metal (MIM) structure. In this case, the electrical conductance of the device, acting as the strength of the synapse, can be modulated using electrical stimulations [3-4]. Even though different synaptic behaviors are readily demonstrated using different combinations of metals and insulators, the emulation of both LTP and STP in a single device, with good control over the relaxation process and transition between the two behaviors, remains a challenge. In fact, residual charges can accumulate in the insulator during its operation, resulting in inconsistent relaxation process with large variations in terms of relation time. As a consequence, several researchers used multiple devices to emulate LTP and STP leading to area inefficiency and high power consumption [5]. Writing in *Nature Electronics*, H. -S. Philip Wong and colleagues at Stanford University, Soochow University and The Hong Kong Polytechnic University showed that the emulation of both STP and LTP characteristics with ultra-low power consumption is possible in vertical MIM-like synapses using multilayer hexagonal boron nitride (*h*-BN) sheets as RS medium [6].

Previous studies have shown MIM-like electronic synapses using 2D materials [7-8]; however, planar configurations have been used which occupy much larger area than vertical architectures. Additionally, previous works have synthesized the 2D materials using mechanical exfoliation which is not a scalable method. Using chemical vapor deposition (CVD), Wong *et al.* have effectively grown large-area multilayer *h*-BN sheets with layered area of over 90%. This has been confirmed using 80 consecutive TEM images covering a total length of 3 µm. Different combinations of metals have been studied in the MIM structures and the results show low synapse-to-synapse variability during the forming process. A novel approach that uses ionic-liquid (IL) electrode has been applied during the formation process. Conducting atomic force microscopy (CAFM) based study showed the formation of several 20-30 nm wide conductive nano-filaments. Next, using electron energy loss spectroscopy (EELS) measurements, the authors also demonstrated a new switching mechanism in their devices where B-vacancies are generated and filled by metal ions from the adjacent electrodes, a switching mechanism that is distinct from those observed in typical ReRAM and CBRAM.

Moreover, ultra-low power consumption of 0.1 fW in standby mode and 600 pW per transition have been achieved in the volatile RS synapses with the 15-18 layer thick *h*-BN stack. While previous studies have shown slow erratic relaxation mechanism in their devices (relaxation time of 0.1-100 s), in this work, a fast and stable relaxation process (relaxation time of 200 µs) has been shown during more than 500 cycles.

This work represents an important advancement for the development of electronic synapses in terms of performance, energy efficiency and potential scalability. The results presented by *Wong et al.* show that vertical MIM-like synapses with (*h*-BN) sheets could become the devices of choice in neuromorphic computing applications.



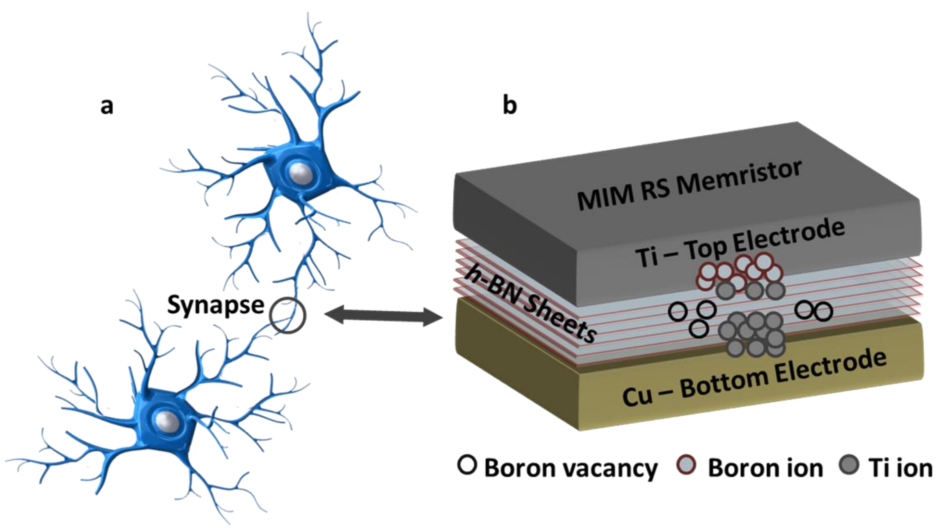


Fig. 1: Synaptic behavior in RS in metal/*h*-BN/metal devices. a Schematic illustration of a biological synapse. b, The switching mechanism in the MIM RS structure with *h*-BN sheets. Metallic ions penetrate the electrode and generate B-vacancies.

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