Diffusive memristor based artificial synapses and neurons

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The hardware implementation of neuromorphic computing calls for emerging devices with good scalability and energy efficiency [1]. Diffusive memristors with Ag active metal species are volatile threshold switches featuring spontaneous rupture of conduction channels. The unique temporal dynamics of the conductance evolution, originating from the underlying electrochemical and diffusive dynamics of the active metals, has enabled faithful emulation of synaptic plasticity with relaxation process [2]. The delay in metallic filament formation could simulate leaky integrate-and-fire and lead to unsupervised learning in a fully memristive neural network.

To investigate the physics of the threshold switching, a planar Au/SiO_xN_y:Ag/Au diffusive memristor was fabricated with a nano-junction. (**Fig. 1a**) The *in-situ* HRTEM images (**Fig. 1b**) show the filament was formed with voltage induced electrochemical growth of Ag nanoparticles within the gap. After power off, the conducting bridge of nanoparticles contracted from a wire to a sphere, implying the minimization of the interfacial energy between the Ag nanoparticles and the dielectric serves as the driving force of the relaxation dynamics.

The diffusive memristor, in its vertical stack, has been used to emulate synapse with both short- and long-term synaptic plasticity demonstrated. It exhibited paired-pulse depression (PPD) and the transition to paired-pulse facilitation (PPF) once the rate of the stimulation pulses was increased. (**Fig. 2a**). The facilitation turned into depression with excessive high frequency pulses due to the gradual depletion of Ag at one electrode and accumulation at the other. The depression was intensified with the reduced spiking frequency. In addition, being paired with nonvolatile drift memristors, the spiking-timing-dependent plasticity (STDP) with non-overlapping spikes has been demonstrated using the relaxation dynamics of the diffusive memristor to time the interval between pre- and post-synaptic spikes. (**Fig. 2b**)

With sufficient parallel capacitance, the diffusive memristor could serve the role of an ion-channel near the soma, with membrane capacitance and axial resistance represented by a capacitor C_m and a resistor R_a. (**Fig. 3a**) The charge up of membrane capacitance increases the voltage across the diffusive memristor. Once the threshold is reached, the diffusive memristor is switched ON, which discharges the capacitor (**Fig. 3b**), mimicking the leaky integrate-and-fire properties of biological neurons.

A prototypical memristor neural network with diffusive memristor neurons and drift memristor synapese was built (**Fig. 4a**)[3], where Pd/HfO_2/Ta drift memristors were in series with transistors. (**Fig. 4b**) The junction of diffusive memristor is illustrated in **Fig. 4c**. Unsupervised synaptic weight update was demonstrated with lateral inhibition between neurons to enhance the discrimination of the inputs. (**Fig. 4d-f**) The initial conductance of synapses concentrated around ~100μS. The synapses were programmed by the simple STDP rule and gained similarity with the means of input patterns which triggered firing of the associated neurons.

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[2] Z. Wang, S. Joshi, S.E. Savel'ev, H. Jiang, R. Midya, P. Lin, M. Hu, N. Ge, J.P. Strachan, Z. Li, et al, Nat. Mater., **16**, 101 (2017)

[3] Z. Wang, S. Joshi, S.E. Savel'ev, W. Song, R. Midya, Y. Li, M. Rao, P. Yan, S. Asapu, Z. Ye, et al, Nat. Electron. (In Press)

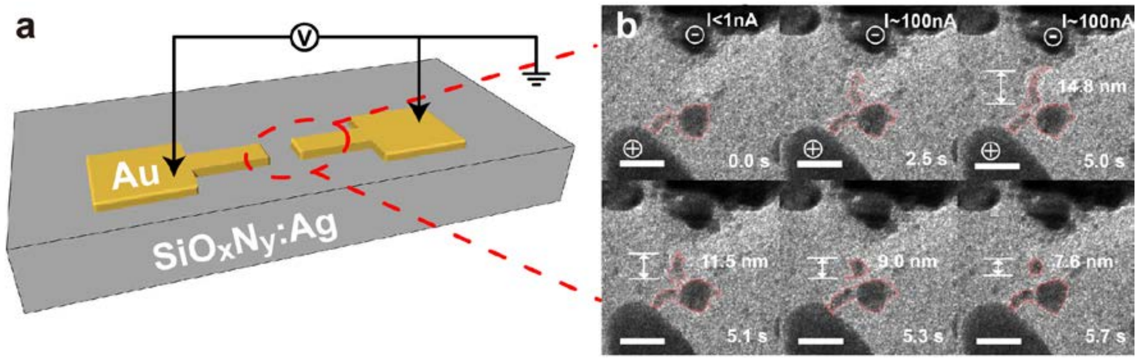

*Figure 1: **(a)** Schematic of ~~the~~ a lateral Au/SiO$_x$N$_y$:Ag/Au diffusive memristor with two Au electrodes embedded in the dielectrics, and the measurement circuit. **(b)** In situ TEM observation of the threshold switching of the lateral diffusive memristor. Voltage was applied at time zero. Ag nanocrystals formed and bridged the electrodes at 2.5s. When the voltage was switched OFF at 5.0s, the filament started to deform and shrink to a round spherical nanocluster, suggesting the relaxation is a diffusion process driven by interfacial energy minimization. All scale bars, 20nm.*

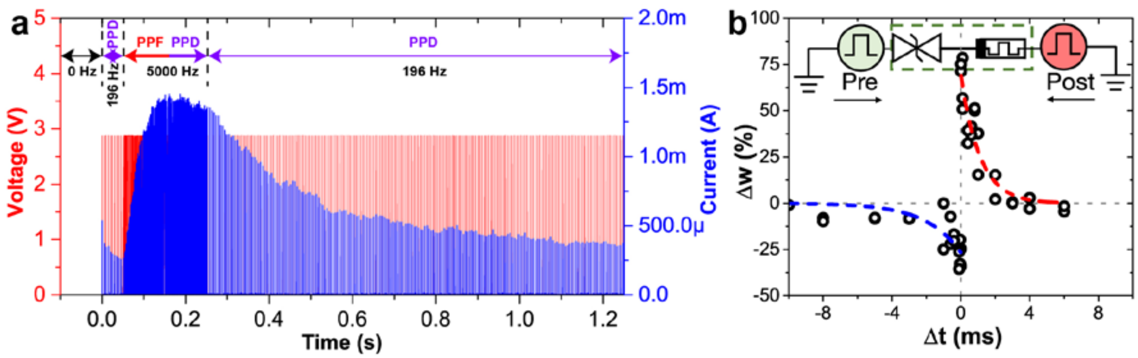

*Figure 2: **(a)** Experimental observation of short-term synaptic plasticity of the diffusive memristor. The device showed PPD upon low frequency stimulation and then PPF with increased stimulation frequency. The brief facilitation was followed by depression again because of the depletion of Ag. **(b)** The conductance (weight) change of the drift memristor synapse in series with a diffusive memristor, as a function of the interval between pre- and post-synaptic spikes, showing bio-realistic STDP.*

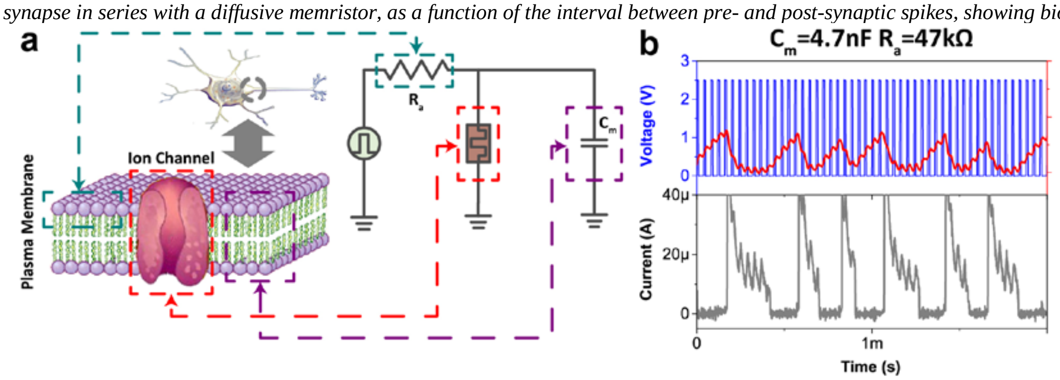

Figure 3: **(a)** *Illustration of the analogy between a biological neuron and a diffusive memristor based artificial neuron. The pre-synaptic inputs are integrated on the capacitance of the membrane (or equivalently C_m) and the ion channel (or equivalently diffusive memristor) opens if the threshold condition is reached. **(b)** Response of the integrate-and-fire circuit to consecutive pre-synaptic spikes. The current pulse across the diffusive memristor coincided with the discharge of the capacitor indicating that the circuit actively fired a pulse of stored charge.*

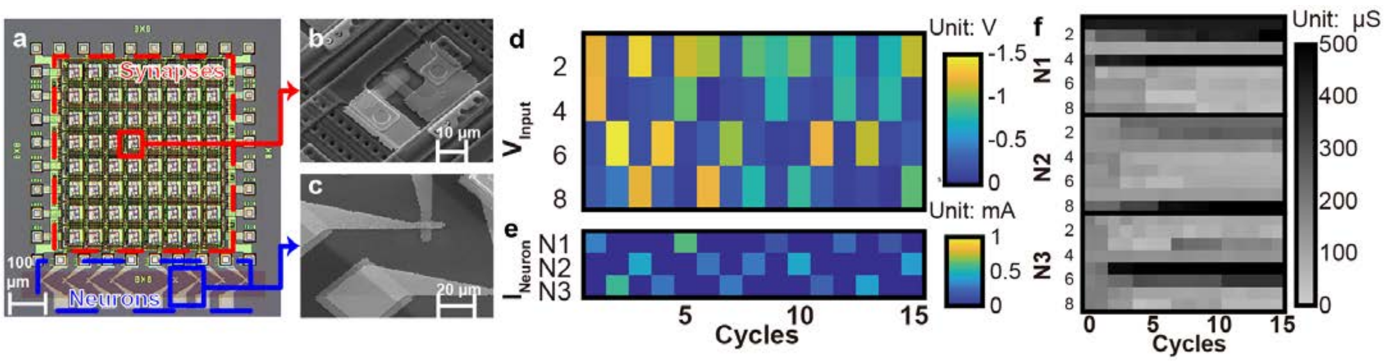

*Figure 4: **(a)** Optical micrograph of the integrated memristive neural network. The 8×8 1-transistor-1-drift-memristor (1T1R) crossbar array interfaced with 8 diffusive memristor artificial neurons with external capacitors. **(b-c)** Scanning electron micrographs of a single 1T1R cell and diffusive memristor junction, respectively. **(d-f)** The input patterns (peak voltages of waveforms), peak neuronal currents, and synaptic weights at each training cycle of the unsupervised weight update, respectively. The weight of synapses was initial ~100μS and gained similarity with input patterns which triggered the plasticity of the associated neurons.*