# Electronic Supplementary Information

# Phase-change Nano-clusters Embedded Memristor for Simulating Synaptic Learning

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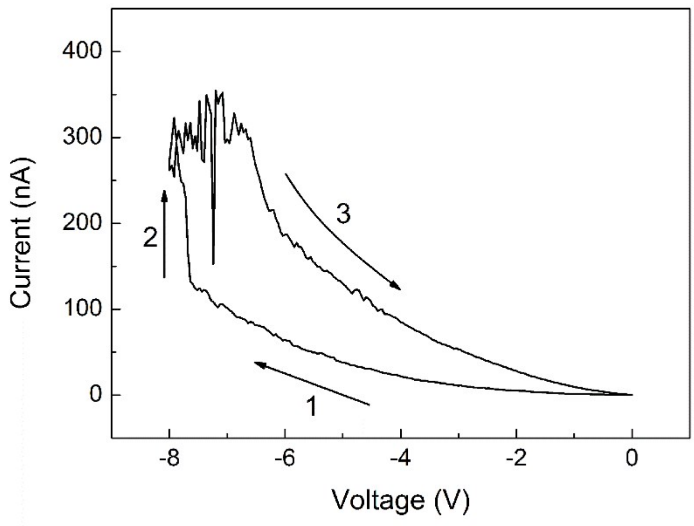


Fig. S1 Forming process of sample 1 with the Al:Nb ratio of 1.3.

Fig. S1 shows the forming process of sample 1 by loading voltage to -8 V. The current jumps abruptly after -7 V. The current peak does not synchronize with the voltage maximum during a sweep cycle. It appears during the -8 V to 0 V period.

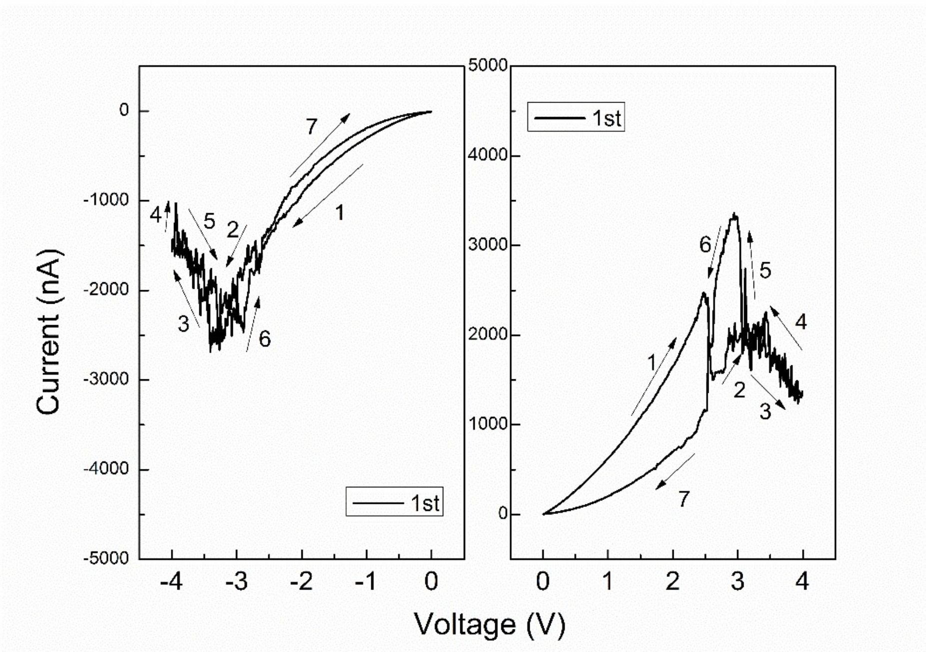


Fig. S2 The I-V curve of sample 2 with the Al:Nb ratio of 0.3.

Fig. S2 show the I-V curve of sample 2 with the Al:Nb ratio of 0.3. The arrow in the figure presents the direction of voltage sweeping. One can see that the I-V property is quite more complicated and instable than that of the sample with Al:Nb ratio of 1.3. There might be big pure Nb cluster formed during the deposition. Controlling the content and precipitate of Nb is challengeable. We limit our study on the sample with lower Nb content in this paper.

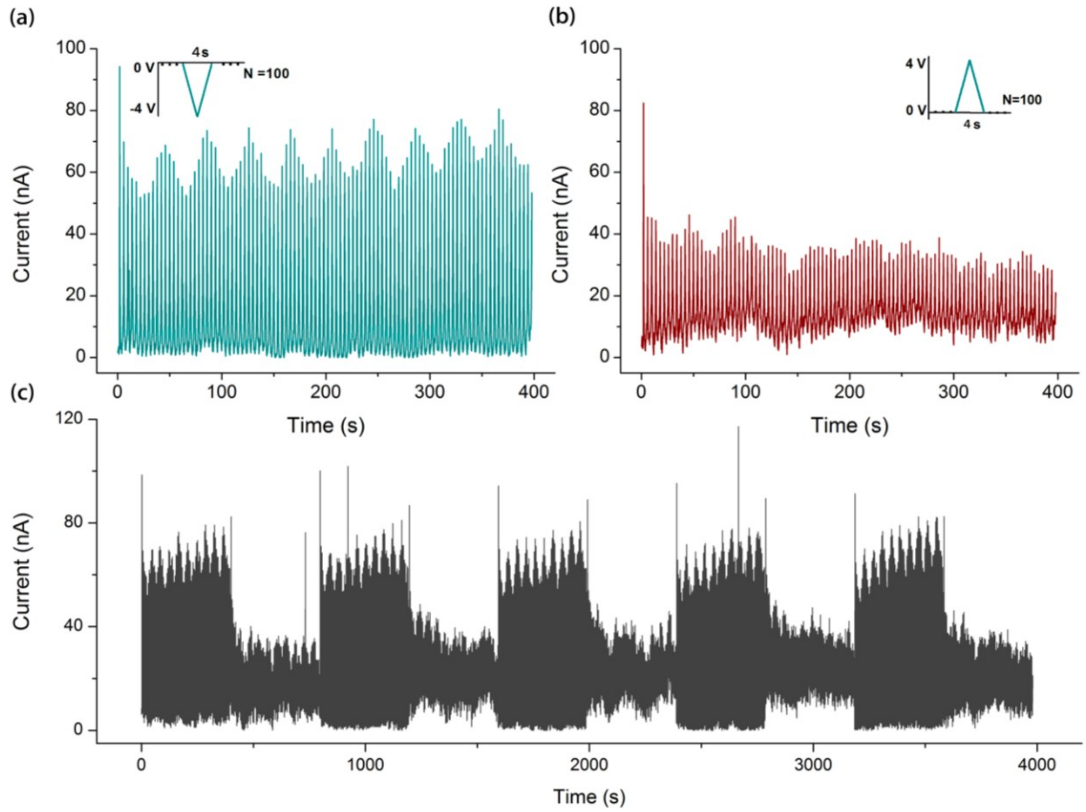


Fig. S3 Complete I-V properties under consecutive voltage sweeps. The absolute value of the maximum voltage is 4 V, the sweep rate is 2 V/s and the reading interval is 20 ms. (a)100 negative voltage sweeps and (b) 100 positive voltage sweeps. (c) 1000 consecutive voltage sweeps are arranged in a series of 5 × (100 negative sweeps + 100 positive sweeps).

Figs. S3a and S3b are the complete I-V properties of 100 voltage sweeps with amplitude of – 4 V and + 4 V, respectively. The current peaks during a sweep and the current values at the voltage maximum are extracted and plotted Figs. 3d and 3e, respectively. Fig. S3c shows the response current varied with times under a thousand of consecutive voltage sweeps arranged in a series of 5× (100 negative and 100 positive sweeps), which is used to examine the stability and endurance of the memristor. The current peaks ($I_P$) in each sweep are extracted and plotted in Fig. 1f.

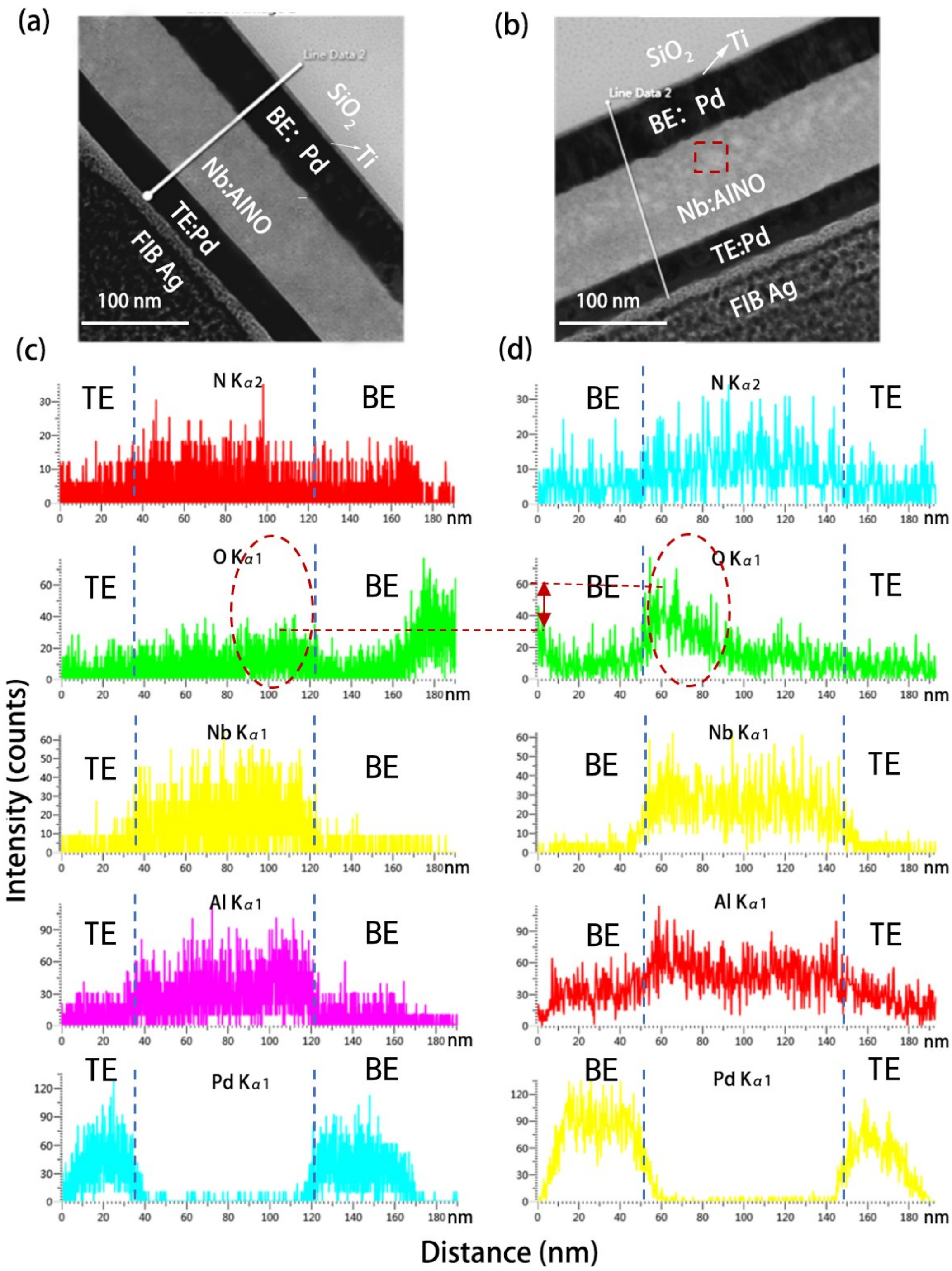


Fig. S4 The TEM cross-sectional images of the memristor (a) in the initial state, and (b) in high resistance state (HRS), respectively. (c) and (d) The variations of N, O, Nb, Al, Pd element contents along the lines marked in (a) and (b), respectively, which are obtained by using energy dispersive X-ray (EDX) spectra.

Figs. S4a and 4b show the transmission electrical microscopy (TEM) cross-sectional images of the memristor's in the initial state and high resistive state (HRS) shown in Fig. 4g, respectively. Figs. S4c and S4d reveal the variations of several element contents cross over the arbitrary cross-sectional (the lines marked in Figs. S4a and S4b, respectively) by using energy dispersive X-ray (EDX) spectra. Though the resolution of EDX is limited, the relative element variations can be analyzed. Comparing Fig. S4c with Fig. S4d, we can find that the oxygen content is slightly higher in the zone near the bottom electrode (BE). Since the bright spots distribute clearly near the BE, we can conclude that the new phase with bright contrast has higher oxygen content, and that the oxygen vacancies migrate to the top electrode under the negative bias. When the positive bias is loaded, the oxygen vacancy begins to move to the direction of BE and neutralize parts of oxygen ions along the filament to result in rupture of filament.

Table S1. Linear fitting of Figs. 4b and 4c.

| | **Frequency** | **Fitting formula** |
|---|---|---|
| **1** | 1 Hz | $W = 93.06234-0.0391* N$ |
| **2** | 5 Hz | $W = 88.54294+0.04246* N$ |
| **3** | 10 Hz | $W = 90.83944+0.07788* N$ |
| **4** | 20 Hz | $W = 99.20139+0.00306* N$ |
| **5** | 40 Hz | $W = 100.17092-0.01276* N$ |
| **6** | 60 Hz | $W = 78.72719+0.15405* N$ |
| **7** | 80 Hz | $W = 92.13129+0.11096*N$ |