Supporting Information

Memristors based in $NdNiO_3$ nanocrystals film as sensory neurons for neuromorphic computing

Jianhui Zhao[1#], Yunfeng Ran [1#], Yifei Pei,[2] Yiheng Wei,[1] Jiameng Sun,[1] Zixuan Zhang,[1] Jiacheng Wang,[1] Zhenyu Zhou,[1] Zhongrong Wang,[1] Yong Sun,[1] Xiaobing Yan [1*]

[1] Key Laboratory of Brain-Like Neuromorphic Devices and Systems of Hebei Province, College of Electronic and Information Engineering, Hebei University, Baoding 071002, People's Republic of China.
[2] Hebei Key Laboratory of Optic-Electronic Information Materials, College of Physics Science and Technology, Hebei University, Baoding 071002, People's Republic of China.

TABLE S1 The Set Power of Different Mott insulator materials uses as TS device.

Structure	Set Power	Reference
$Si/SiO_2/TiN/Pt/NbO_2/SiO_2/Pt$	~ 2.6 mW	[1]
$Pt/SiO_2/Si/SiO_2/VO_x/W$	~ 100 μW	[2]
$Si/Pt/NbO_x/Pt$	~ 50 μW	[3]
$TiN/NbO_2/W$	~ 7.5 μW	[4]
$Pt/NbO_x/Pt$	~ 200 μW	[5]
$W/NbO_2/W$	~ 40 μW	[6]
$TiN/ZrO_2/NbO_2/Pt$	~ 5 μW	[7]
Pt/VO_2 nanochannel/Pt	~ 0.5 mW	[8]
$Pd/NdNiO_3$/n-Si	120nW	This work

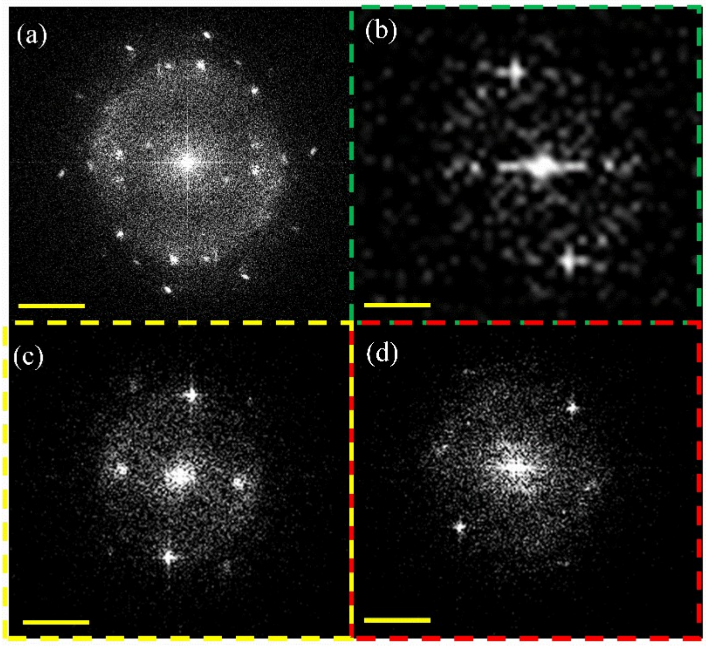

Figure S1. The fast Fourier transform (FFT) of the selection area in Fig.2c.

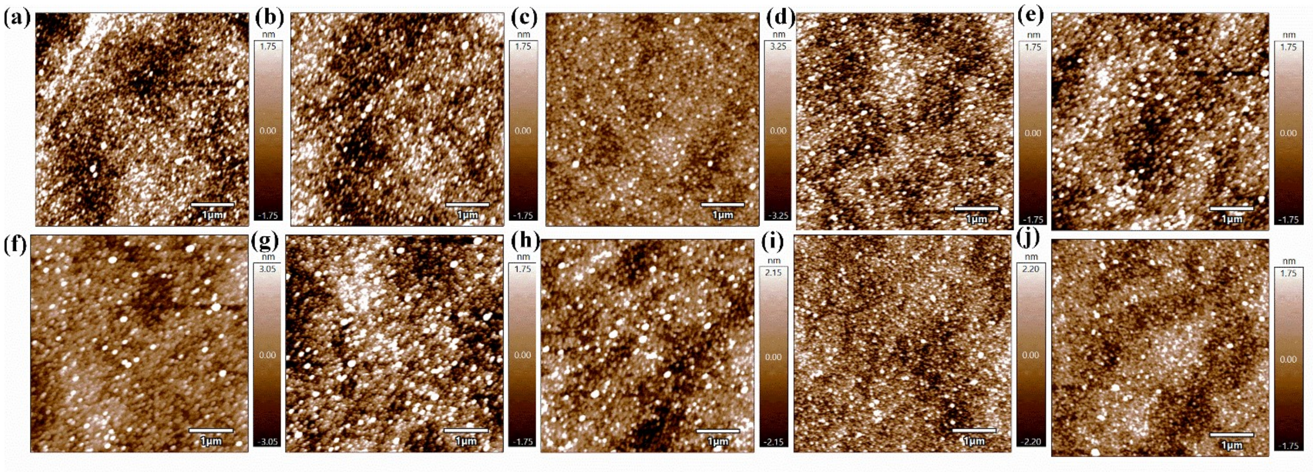

Figure S2. AFM images of 10 areas of NNO film.

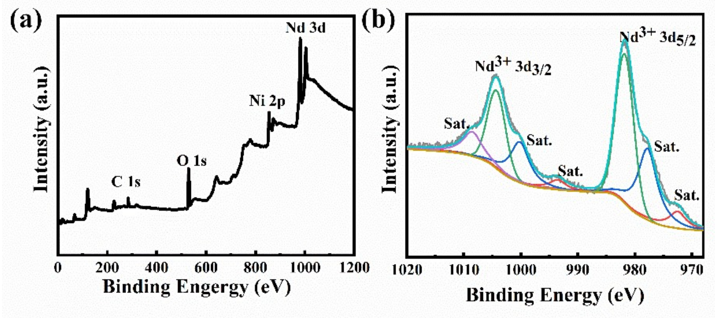

Figure S3. (a) X-Ray Photoelectron Spectroscopy diagram. (b) X-Ray Photoelectron Spectroscopy diagram of Nd 3d

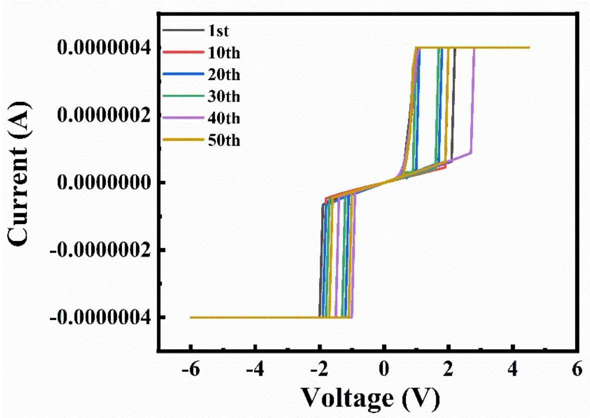

Figure S4. The I-V curves for 1, 10th, 20th, 30th, 40th, 50th.

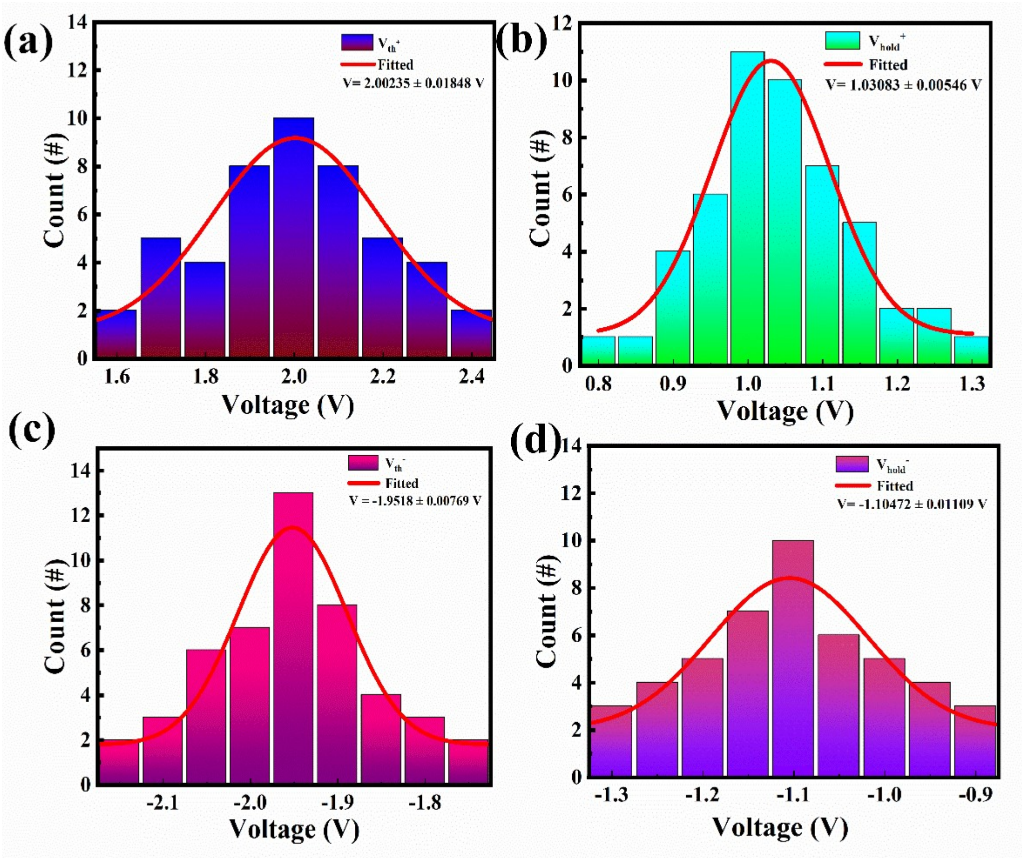

Figure S5. (a)(b)The distribution of the positive threshold/hold voltage, respectively.(c)(d) The distribution of the negative threshold/hold voltage , respectively.

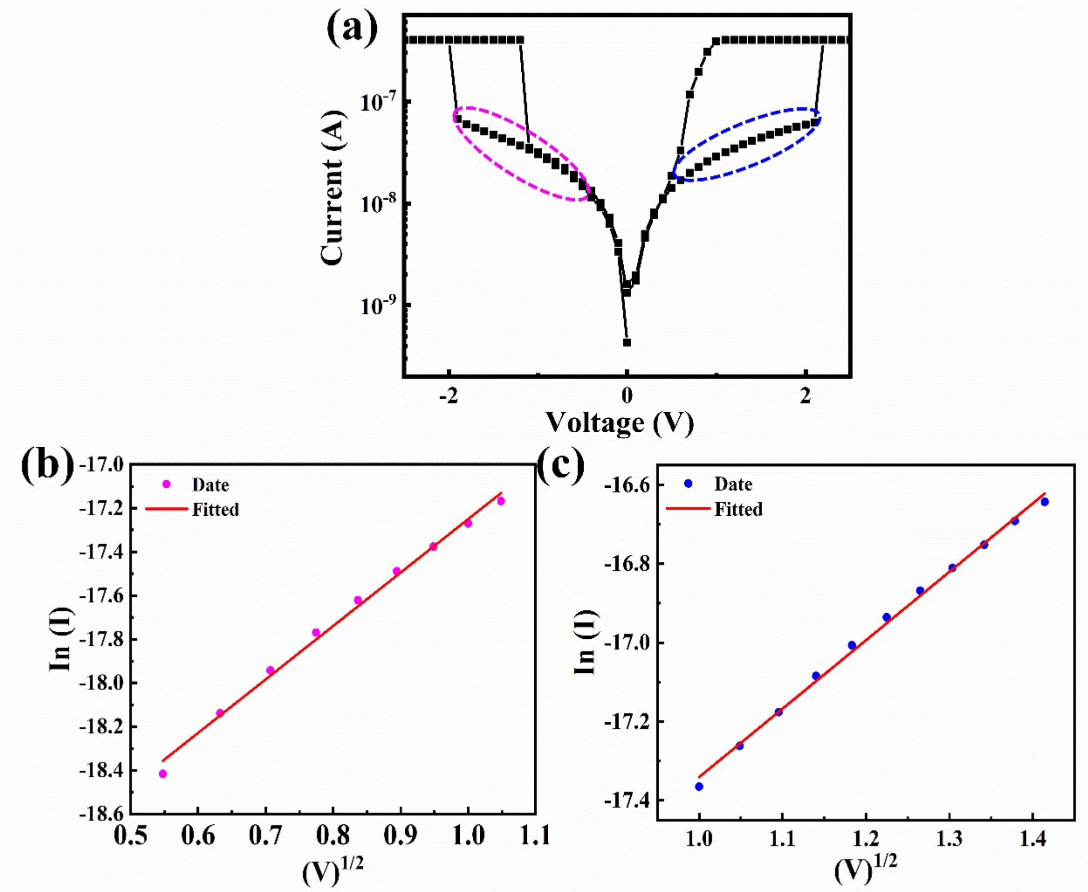

Figure S6. I-V curves detailing the phenomenon of decreasing resistance of HRS and the result of conduction mechanism.

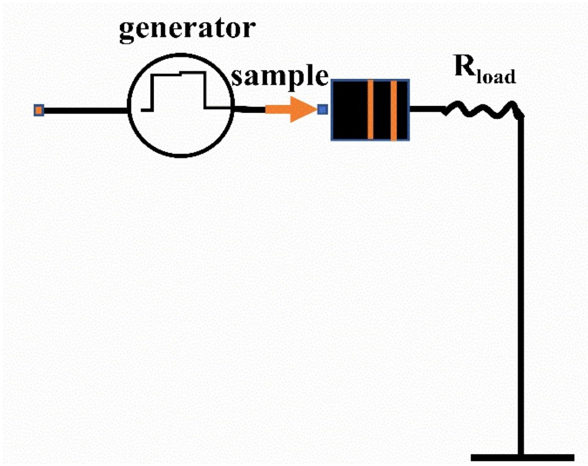

Figure S7. Test circuit.

Supplementary Note S1

The energy required to turn on a device should be fixed in theory, but the energy is different on the same voltage in different modes.[9, 10] In the current-voltage (IV) curve in Fig. 2 in main body, it is the direct-current (DC) sweep voltage mode, where the energy could be accumulated from the voltage applied in Fig. S8a and 20 ms for each step-time. This long-time applied voltage and cumulative effect lead to a low (2 V) set voltage in DC sweep testing mode. In the Fig. 4 and Fig. 5 of main body, the applied voltage is in pulse mode shown in Fig. S8b. In pulse mode, the voltage is applied to the device at certain intervals, which will lead to the loss of some energy applied to the device, and the pulse width is much smaller than the DC sweep mode. Therefore, a larger applied voltage is needed in Fig. 4 (4 V) and Fig. 5 (5 V). The Fig. 5 is the LIF neuron circuit shown in Fig. S8c, where the output pulse energy will be consumed not only by the TMS, but also by the capacitor and the resistance in the circuit. Compared to pulse mode, it needed to apply a larger voltage to set the TMS in the LIF neuron circuit in Fig. 5 than Fig. 4. To sum up, the LIF neuron circuit needs the maximum applied voltage, and the sweep mode needs the minimum applied voltage.

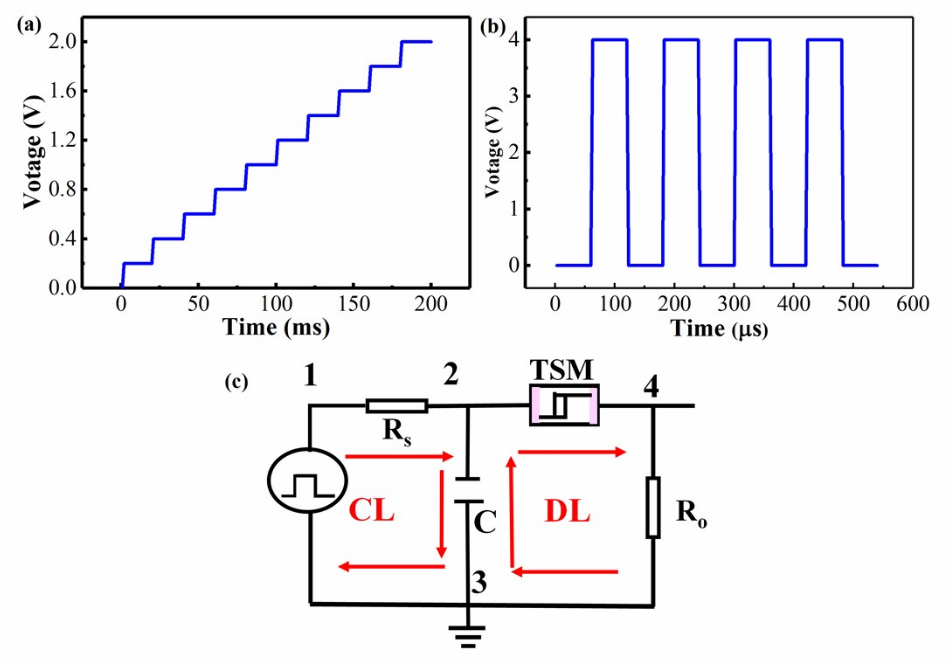

Fig. S8 (a) The sweep mode of applied voltage. (b) The pulse mode of applied voltage. (c) The LIF neuron circuit.

Supplementary Note S2

The memristor is a passive device with the dimension of resistance, which follows the principle of voltage division in the circuit.[11] Therefore, the output voltage depends on the input voltage of the signal and the partial voltage of the device in the circuit. Fig. 6a in main body adjusts the firing frequency of neurons by changing the series resistance Rs of the circuit in Fig. S8. The smaller the resistance value of the series resistor (Rs), the smaller the partial voltage across it, and the higher the voltage applied to both ends of the device. This results in a higher output voltage. When all circuit components remain unchanged and only the pulse voltage is changed, the higher the applied pulse voltage, the higher the voltage allocated to each component, and the higher the output voltage. Therefore, the amplitude of the output voltage is affected by the resistance value of the series resistor and the applied voltage amplitude.

Reference

1. M. Kang and J. Son, *Applied Physics Letters*, 2016, **109**, 202101.
2. K. Zhang, B. Wang, F. Wang, Y. Han, X. Jian, H. Zhang and H. Wong, *IEEE Electron Device Letters*, 2016, **37**, 978-981.
3. J. Zhu, Z. Wu, X. Zhang, Y. Wang, J. Lu, P. Chen, L. Cheng, T. Shi and Q. Liu, presented in part at the 2021 5th IEEE Electron Devices Technology & Manufacturing Conference (EDTM), Chengdu,China, 2021.
4. E. Cha, J. Park, J. Woo, D. Lee, A. Prakash and H. Hwang, *Applied Physics Letters*, 2016, **108**, 153502.
5. L. Gao, P.-Y. Chen and S. Yu, *Applied Physics Letters*, 2017, **111**, 103503.
6. D. Lee, M. Kwak, K. Moon, W. Choi, J. Park, J. Yoo, J. Song, S. Lim, C. Sung, W. Banerjee and H. Hwang, *Advanced Electronic Materials*, 2019, **5**, 1800866.
7. A. Chen, Y. He, G. Ma, Z. Zhang, J. Ji, J. Wan, J. Zhang, H. Wan, L. Tao, Y. Rao, L. Shen, H. Wang, J. Zhang, Y. Wang, T.-C. Chang, P. A. van Aken and H. Wang, *Applied Physics Letters*, 2021, **119**, 073503.
8. W. Xue, G. Liu, Z. Zhong, Y. Dai, J. Shang, Y. Liu, H. Yang, X. Yi, H. Tan, L. Pan, S. Gao, J. Ding, X. H. Xu and R. W. Li, *Adv Mater*, 2017, **29**, 1702162.
9. X. Yan, L. Zhang, H. Chen, X. Li, J. Wang, Q. Liu, C. Lu, J. Chen, H. Wu and P. Zhou, *Adv. Funct. Mater.*, 2018, **28**, 1803728.
10. X. Yan, J. Zhao, S. Liu, Z. Zhou, Q. Liu, J. Chen and X. Y. Liu, *Advanced Functional Materials*, 2018, **28**, 1705320.
11. D. B. Strukov, G. S. Snider, D. R. Stewart and R. S. Williams, *Nature*, 2008, **453**, 80-83.