# Electronic supplementary information

**New Application of Carbon Quantum Dots in Memristor**

Yifei Pei,[a] Zhenyu Zhou,[a] Andy Paul Chen,[b] Jingsheng Chen,[b] and Xiaobing Yan,[a*]

[a] *National-Local joint engineering laboratory of new energy photovoltaic devices, College of Electron and Information Engineering, Hebei University, Baoding 071002, P. R. of China*

*E-mail: yanxiaobing@ime.ac.cn*

[b] *Department of Materials Science and Engineering, National University of Singapore, Singapore 117576, Singapore*

Keywords: carbon conductive filaments, quantum dots, associative learning activities, resistive switching, digits recognition

I Supporting Figures:

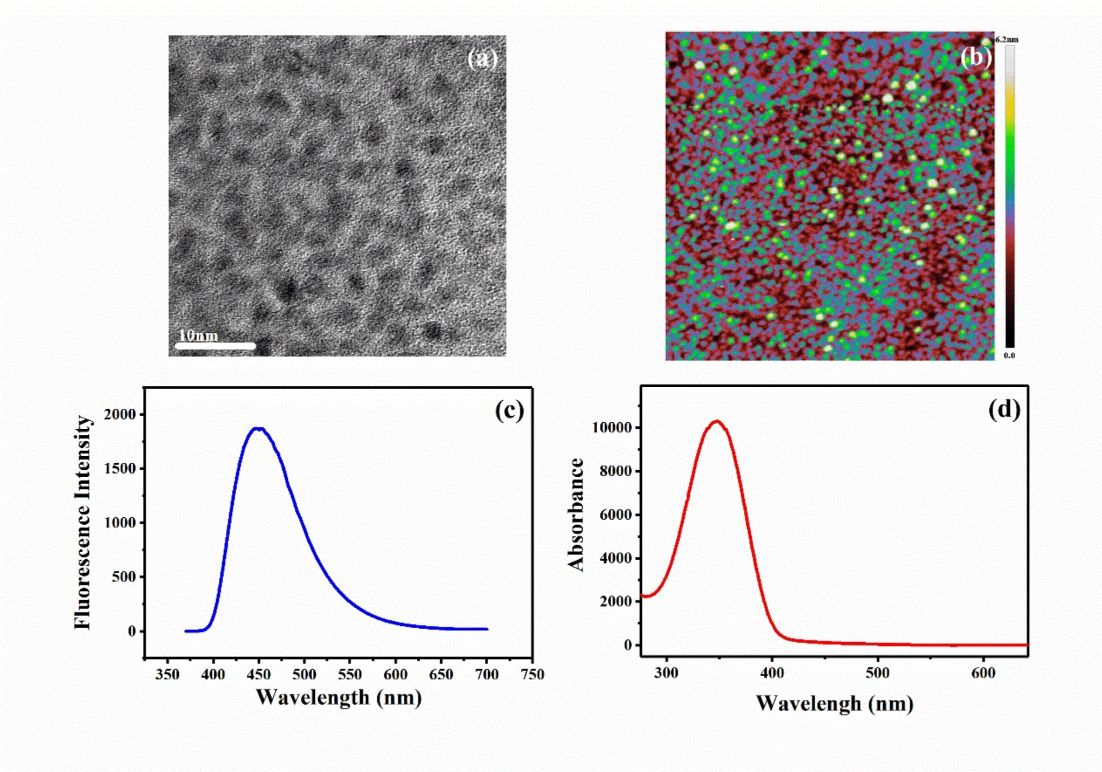


**Figure S1.** a) TEM images of carbon QDs liquid. b) AFM images of carbon QDs films in CMD. c) The fluorescent emission spectra of carbon QDs liquid. d) The UV visible absorption spectrum of carbon QDs liquid.

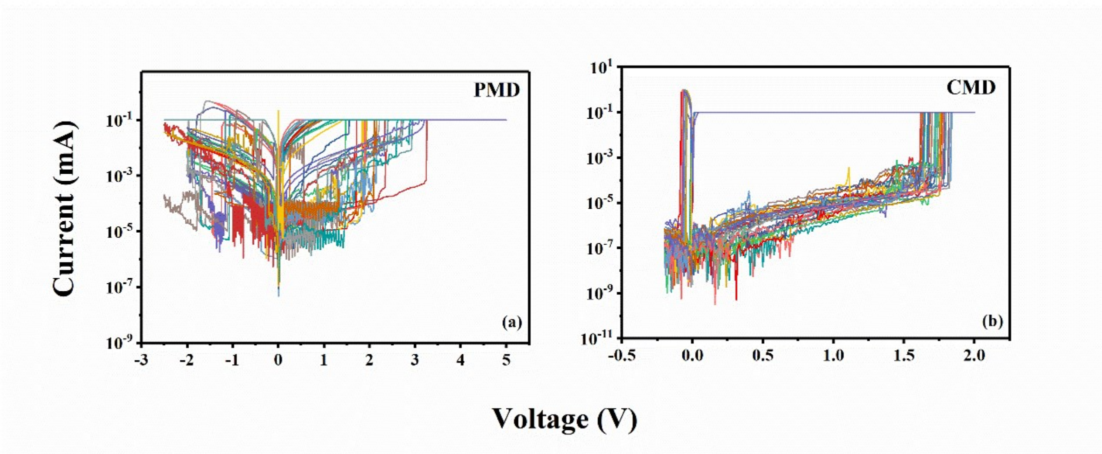


**Figure S2.** a) Endurance in different batches of PMD. b) Endurance in different batches of CMD. c) Forming program of PMD. d) Forming program of PMD.

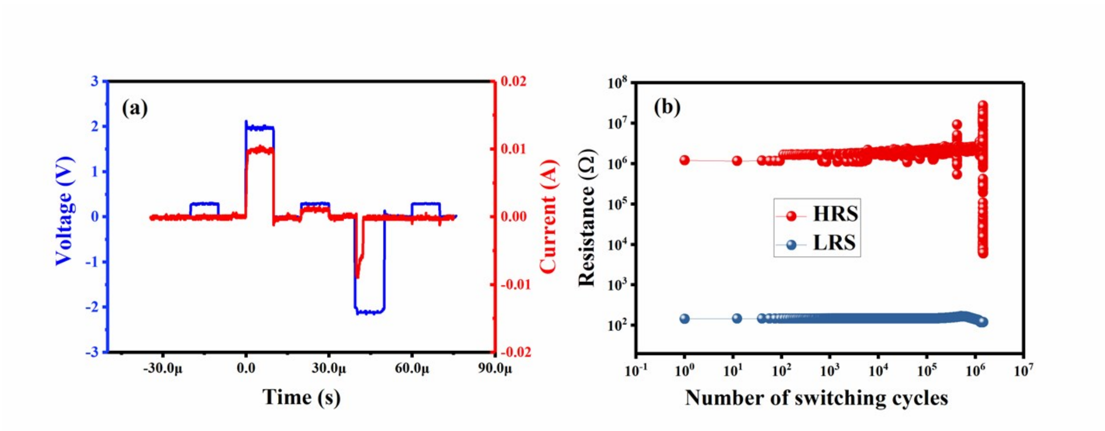


**Figure S3.** a) Measured the endurance properties with 10 μs pulse. b) CMD can achieve $10^6$ cycles.

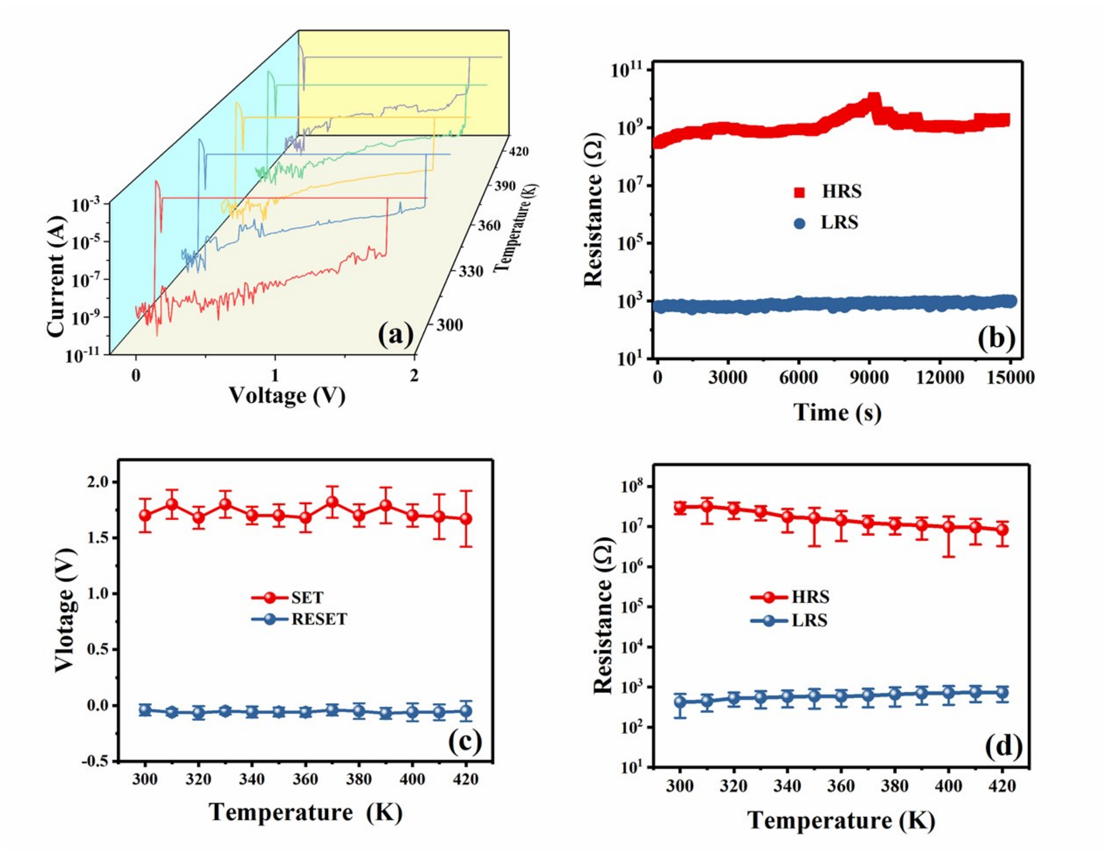


**Figure S4.** a) Temperature dependence of I-V curves from 300K to 420K, b) Retention characteristics at 420K, c) Switching voltage statistics at different temperatures with error bar. d) HRS and LRS statistics at different temperatures with error bar.

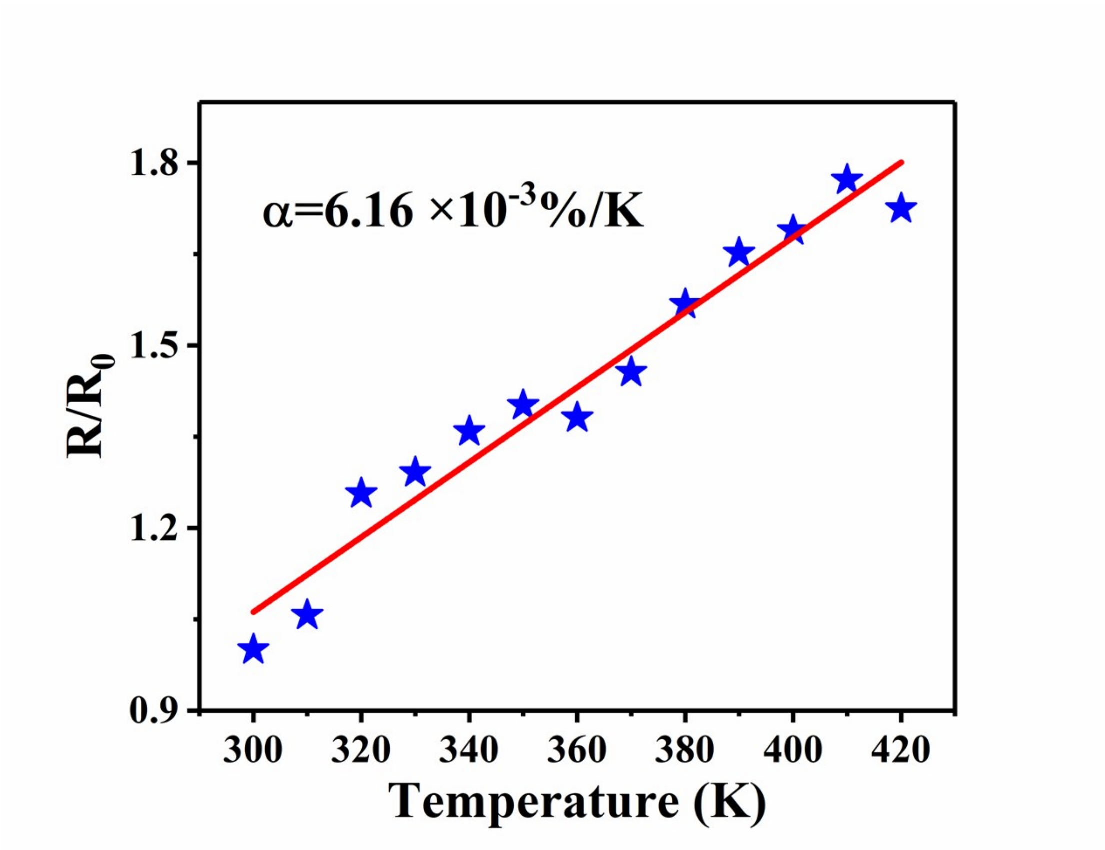


**Figure S5.** Relationship between R/$R_0$ in LRS and temperature.

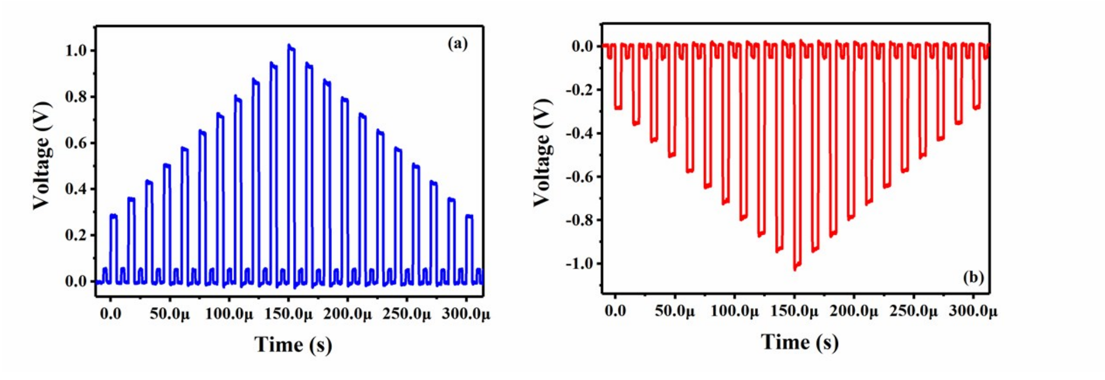


**Figure S6.** The single pulse group of eight continuous scans from positive and negative directions.

## II Conduction mechanism of the CMDs

The tunneling current can be expressed as followed equation according to the TAT conductance theory [1, 2]

$$I = N \bullet q \bullet v \tag{S1}$$

Here, $N$ is the total number of traps that help conduct electricity, and $v$ is the transition rate, which can be written as

$$v = v_0 \bullet f \bullet P \tag{S2}$$

Here, $v_0$ is the frequency factor, and $f$ = 1/ [1 + exp (($E_b - E_t + F \cdot d$)/kT)] is the electrons Fermi–Dirac distribution in interior of the electrode. $E_b$ is the barrier heigh, and the product of the Boltzmann constant and temperature is kT. The transmission probability $P$ is shown as

$$P = exp\left\{ -\frac{4}{3\hbar qF}\sqrt{2m_c\left[E_t^{3/2} - (E_t - F \bullet d)^{3/2}\right]}\right\} \tag{S3}$$

Here, $\hbar$, $q$, $F$, $d$, $E_t$ is the reduced Planck's constant, electronic charge quantity, electric field intensity, tunneling distance, and defect-trap energy below CB, respectively. [3]

## III STDP learning function

$$\xi = \begin{cases} A_+ \exp\left(-\frac{\Delta t_{post-pre}}{\tau_+}\right) & (\Delta t_{post-pre} > 0) \\ -A_- \exp\left(-\frac{\Delta t_{post-pre}}{\tau_-}\right) & (\Delta t_{post-pre} < 0) \end{cases} \tag{4}$$

where $A_+$ and $A_-$ were defined as the maximum synaptic strength modification when $\Delta t_{post\text{-}pre}$ is near zero. $\tau_+$ and $\tau_-$ are learning windows determining .

## IV Simulates the PPF functions of biological synapses

Paired-pulse facilitation (PPF) phenomenon means an increase in the synaptic weight upon decreasing the interval between two continuous pulses. [4] The pulse waveform is shown in the inset of Fig. S7. And the PPF results is shown in Figure S7. The PPF ratio is defined by

$$PPF = \frac{G_2 - G_1}{G_1} \times 100\% = C_1 \times e^{\frac{-t}{\tau_1}} + C_2 \times e^{\frac{-t}{\tau_2}} \tag{6}$$

Here, $G_1$ and $G_2$ are the conductance values after the first and second pulses, respectively. [5] The two time constants can be fitted $\tau_1$ (28 μs) and $\tau_2$ (37 μs), which relevant to fast and slow decaying terms, respectively. It can be found from the fitting equation that smaller interval can cause the memory effect reinforced, which agree with the biological synapse.

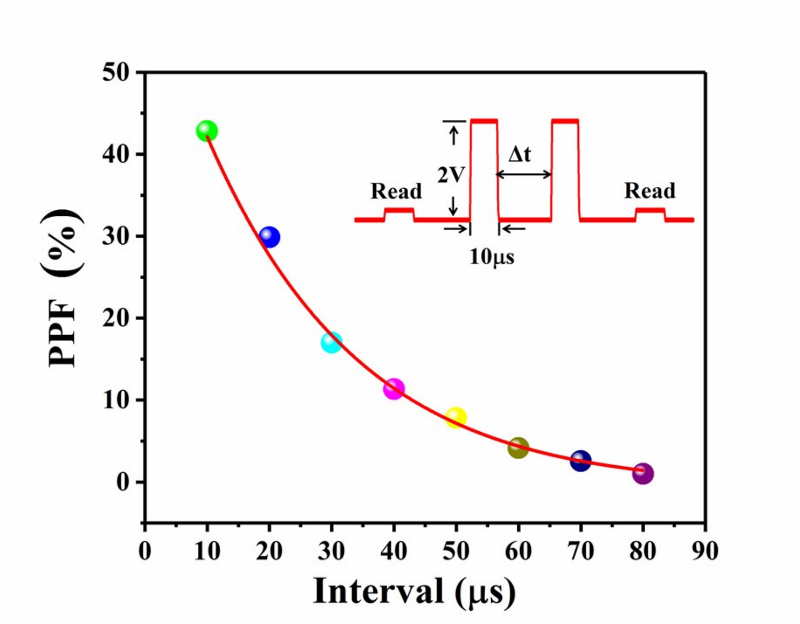


**Figure S7.** PPF characteristics of CMD and the waveform used for PPF measurement.

V Table 1. Comparison between in Recent Three Years Artificial Memristors Synapses and This Work*

| *Device Structure* | $\delta_{SET/RESET}$<5% | STP to LTP to LTD transition | Number of STDP Types | Associative Learning | Digit or Face Recognition | Journal |
|---|---|---|---|---|---|---|
| *Pd/ carbon QDs/$Ga_2O_3$/Pt* | YES | √ | 4 | √ | √ | This work |
| *Ag/$Ga_2O_3$/PbS QDs/Pt* | No | – | 1 | – | – | Adv. Mater., 2019, 1805284 |
| *Pt (Au)/ $SiO_xN_y$:Ag/Pt (Au)* | No | – | 2 | – | – | Nat. Mater., 2017, 16, 101 |
| *Pt/STO/Nb-STO* | – | √ | 2 | – | – | Adv. Funct. Mater. 2017, 1704455 |
| *ITO/$Al_2O_3$ NP:PI/Ag* | No | – | – | √ | – | Adv. Mater. 2017, 29, 1602890 |
| *Au/Nafion/ITO* | – | – | 2 | – | √ | Adv. Funct. Mater. 2019, 29, 1808783 |
| *Cu/p$V_3D_3$/Al* | – | √ | 1 | – | √ | Nano Lett. 2019, 19, 839 |

*** Symbols " √ " and "–" denote demonstrated and non-demonstrated functions, respectively.**

**References**


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