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Flexible resistive switching bistable memory devices using ZnO nanoparticles embedded in polyvinyl alcohol (PVA) matrix and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)[†]

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The resistive switching memory effects in metal-insulator-metal devices with aluminium (Al) as top electrode (TE) and bottom electrode (BE). A solution processed active layer consisting of zinc oxide (ZnO) nanoparticles embedded in an insulating polyvinyl alcohol (PVA) matrix and polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) has been studied by using flexible polyethylene terephthalate (PET) substrates. The current–voltage (*I*–*V*) measurements of hybrid Al/ZnO–PVA/PEDOT:PSS/Al/flexible PET substrate device exhibited a non-volatile bistable resistive switching behaviour, which is attributed to the trapping, storage and transport of charges in the electronic states of the ZnO nanoparticles. The performance of hybrid device is significantly enhanced over control Al/PEDOT:PSS/Al and Al/ZnO–PVA/Al devices due the presence of PEDOT:PSS polymer. This PEDOT:PSS improves the performance of oxygen ions (holes) migration toward BE and protect back oxygen vacancies (electrons) migrate toward BE from ZnO–PVA composites which may reduces the leakage current, as a result, increased the 'ON state/OFF state' current ratio of 7.9×10^3 times. The fabricated hybrid device showed high ON/OFF switching current ratio larger than five orders of magnitude with low operating voltages. It is observed that, the existence of two conducting states, namely, low conductivity state (OFF state) and high conductivity state (ON state), exhibiting bistable behaviour. The state of the device was maintained even after removal of the applied bias, indicating the non-volatile memory. The observed current–time response showed good memory retention behaviour of the fabricated devices. The excellent stability and retention performances of hybrid device verify the reliability of this device and demonstrate their potential for application in non-volatile bistable memory device. The carrier transport mechanism of the bistable behaviour for the fabricated non-volatile organic bistable devices structures is described on the basis of the *I*–*V* experimental results by analyzing the effect of space charge and electronic structure. Interestingly, the device performance was not degraded and remains identical even after bending the device from 60–120° angles, which indicates high potential for flexible non-volatile bistable memory device applications. This demonstration provides a class of memory devices with the potential for future flexible electronics applications.

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1. Introduction

A mixture of semiconductor nanoparticles and polymers has been particularly interesting due to their potential applications in next-generation electronic and optoelectronic devices.^{1–4} Nanocomposites containing semiconductor nanoparticles and polymer have promising potential applications in non-volatile memory

devices due to their high mechanical flexibility, low cost, and simple fabrication.^{5–8} In memory devices based on nanocomposites, the electrical bistability is primarily determined by the semiconductor nanoparticles.^{9–11} The prospect of applications of non-volatile memory devices utilizing nanocomposites has given rise to extensive research and efforts to develop semiconductor nanoparticles, serving as charging and discharging islands, embedded in a polymer matrix.^{12–18} In the past decade, there are many kinds of advanced non-volatile memory devices have been generated.^{19,20} Among the several types of non-volatile memory devices, the hybrid non-volatile bistable devices have been particularly attractive due to their easier fabrication, less expensive and high flexibility without additional sources and drains.^{21–23} With the

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effort of analyzing current transport behaviour, many studies indicated that semiconductor nanoparticles in such memory devices are responsible for the charge trapping, storage, and emission induced current bistable effect.²⁴ Among the various types of semiconductor nanoparticles, zinc oxide (ZnO) have acted as promising candidates because of their potential applications in non-volatile memory devices and their being environment friendly materials.^{25–29} ZnO is n-type semiconductors with a band-gap of 3.37 eV at 300 K. ZnO based thin film devices have good resistive switching characteristics. It has been extensively studied in both unipolar and bipolar resistive switching behaviour, such as Pt/ZnO/Pt,³⁰ Al/ZnO/Si,³¹ TiN/ZnO/Pt,³² and Cr/ZnO/Pt.³³ Metal/bilayer/metal structure was proposed to improve the performance of the resistive switching behaviour. Lee *et al.*,³⁴ fabricated bilayer $\text{ZrO}_2/\text{HfO}_2$ -based structure to improve resistive switching behaviour. It was observed that, the 'HRS/LRS' ratio increased by 100 times compared to single HfO_2 -based structure. Although there are several reports for the growth of semiconductor nanostructures embedded in polyvinyl alcohol (PVA) polymer matrix, the realization of hybrid ZnO–PVA nanocomposites/conducting polymer model heterostructure used for flexible non-volatile bistable resistive switching memory devices has not been investigated earlier in details. A detail study is necessary for the fabrication of this model heterostructure for possible applications in flexible devices.

In this report, we fabricated and investigated flexible non-volatile bistable memory devices utilizing ZnO–PVA nanocomposites and conducting polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) on an aluminium (Al) coated flexible polyethylene terephthalate (PET) substrates. ZnO is highly suitable material to trap charge carriers due to its appropriate quantum confinement and available energy states. PVA is used as an isolating dielectric material and a supportive layer to transfer the nanoparticles onto the bottom electrodes. Furthermore, PVA is a biocompatible, non-toxic, low cost, environment friendly and non-hazardous organic polymer. PEDOT:PSS is a p-type hole conducting polymer which improved the resistive switching ON/OFF state current ratio of hybrid Al/ZnO–PVA/PEDOT:PSS/Al/flexible PET substrate device by improving the oxygen ions (holes) migration toward BE and protect back oxygen vacancies (electrons) transfer toward BE from ZnO–PVA nanocomposites, which may reduces the leakage current. This work was undertaken to comprehensively explore the resistive switching effect in a hybrid ZnO–PVA/PEDOT:PSS film model heterojunction system as being the potential candidate for the next generation memory device. The fabricated device exhibited a non-volatile and bistable resistive switching behaviour. The carrier transport mechanisms and organic bistable resistive switching behaviour of the ZnO–PVA/PEDOT:PSS model heterojunction system has been demonstrated for potential used in flexible devices.

2. Experimental details

2.1 Synthesis of ZnO nanoparticles

ZnO nanoparticles (NPs) were prepared using sol–gel method.³⁵ In details, 0.01 M of zinc acetate (Merck, 99%) was dissolved in

2-propanal (Merck, 99%) followed by heating and stirring at 65 °C. After 30 minutes, diethanolamine (Nice, 99%) was added to the previous solution, and a transparent solution was achieved. The molar ratio of zinc acetate and diethanolamine was taken as 1 : 2. The solution was kept for half an hour at room temperature. The as grown ZnO NPs were filtered out from the solution and dried in air for further applications.

2.2 Preparation of ZnO–polyvinyl alcohol (PVA) nanocomposites

ZnO–PVA nanocomposite films were prepared by the well known solution casting technique. In this method, 4 gram of solid PVA ($\text{C}_2\text{H}_4\text{O}$)_n (where $n = 1700$) was dissolved in 150 ml of de-ionized (DI) water by heating and stirring at ~95 °C for 2 hours using a magnetic stirrer with hot plate, for complete dissolution without thermal decomposition of the polymer, until the polymer was completely dissolved and a clear viscous solution is formed. The prepared ZnO nanoparticle was added into the aqueous solution of PVA, and then stirred carefully by using magnetic stirrer until well dispersion ZnO–PVA was obtained. For electrical characterizations, different concentration ratios [ZnO NPs (mg) : PVA solution (ml)] of 5 : 1, 8 : 1, 10 : 1, 15 : 1, and 25 : 1 have been studied. Sample with a concentration ratio of 10 : 1 shows superior electrical resistive switching behaviour compared to 5 : 1, 8 : 1, 15 : 1, and 25 : 1 samples, as shown in ESI Fig. SF1.†

2.3 Device fabrication

To produce the device structure, first, aluminum strips were deposited on flexible polyethylene terephthalate (PET) substrate by thermal evaporation through a shadow mask. Second, a conducting polymer, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) (Sigma Aldrich) layer was then spin coated on aluminum (Al) strips with spin speed 1500 rpm. Third, ZnO–PVA nanocomposite solution was deposited onto the PEDOT:PSS layer by spin coated with a spin speed 2000 rpm for 60 seconds. Finally, top aluminium (Al) electrodes were deposited on ZnO–PVA nanocomposite layer by thermal evaporation through a shadow mask.

2.4 Electrical measurements

The electrical characterization of the sandwiched structure was carried out by taking contacts from the Al bottom electrode (BE) and Al top electrode (TE). The active electrode area of the samples was $9 \times 10^6 \text{ m}^2$. For the investigation of the resistive switching behaviour of the fabricated devices, the current–voltage (I – V) characteristics were measured using a source meter (B2912A, Agilent, USA) at room temperature and in a normal environment.

2.5 Sample characterizations

The optical absorption spectra of the samples were recorded in the wavelength range 300–800 nm using a UV-VIS-NIR spectrophotometer (Perkin-Elmer Lambda 950). X-ray diffraction (XRD) spectra were measured by a Bruker D8 ADVANCE diffractometer



3. Results and discussions

3.1 Morphological characterization

The surface topography of PEDOT:PSS films were carried out (scan area 1 mm \times 1 mm) before and after spin coating of ZnO-PVA nanocomposite by atomic force microscopy (AFM) in tapping mode using phosphorous doped silicon cantilever. Fig. 1(a) and (b) show the plane view AFM micrographs of pristine PEDOT:PSS films and ZnO-PVA nanocomposite/PEDOT:PSS heterostructure sample formed on flexible Al coated PET substrates. The surface roughness of the nanocomposite films was determined from AFM topography in 1 mm \times 1 mm area. The RMS surface roughness for pristine PEDOT:PSS films and ZnO-PVA/PEDOT:PSS films were estimated to be 33 nm and 85.3 nm, respectively. The higher surface roughness for ZnO-PVA/PEDOT:PSS film is attributed to the presence of ZnO-PVA nanocomposite. The micrograph

clearly indicates the formation of ZnO nanoparticles (NPs) uniformly distributed in large area. The particle size distribution is plotted at the inset of Fig. 1(b). From the histogram, the diameter of the nanoparticles variation can be estimated as 15–60 nm and the average diameter of the nanoparticles is found to be 35 nm. The average nanoparticle density has been estimated from $1\text{ }\mu\text{m} \times 1\text{ }\mu\text{m}$ surface area and found to be $\sim 3 \times 10^{13}$ NPs per m^2 . Fig. 1(c) represents the typical SEM micrograph of ZnO nanosheets embedded in PVA matrix. It has been observed that ZnO NPs forms nanosheets-like structure inside the PVA matrix. The magnified SEM image of the ZnO nanosheets embedded in PVA matrix as depicted in the inset of Fig. 1(c). It is clearly seen that the SEM micrograph revealed the formation of ZnO nanosheets of thickness 20–40 nm with several micron lengths. Fig. 1(d) shows a cross-sectional view of the grown switching memory structure on flexible Al coated PET substrates. The FESEM micrograph clearly indicates ZnO–PVA nanocomposite, PEDOT:PSS film and Al electrode with sharp interfaces. The thicknesses of the ZnO–PVA nanocomposite and PEDOT:PSS films are estimated to be 100 nm and 180 nm, respectively. Fig. 2(a) represents the typical energy dispersive X-ray (EDX) spectrum of ZnO–PVA nanocomposites. The EDX spectrum confirms the presence of Zn and O elements in ZnO–PVA nanocomposites. The elemental analysis reveals the formation

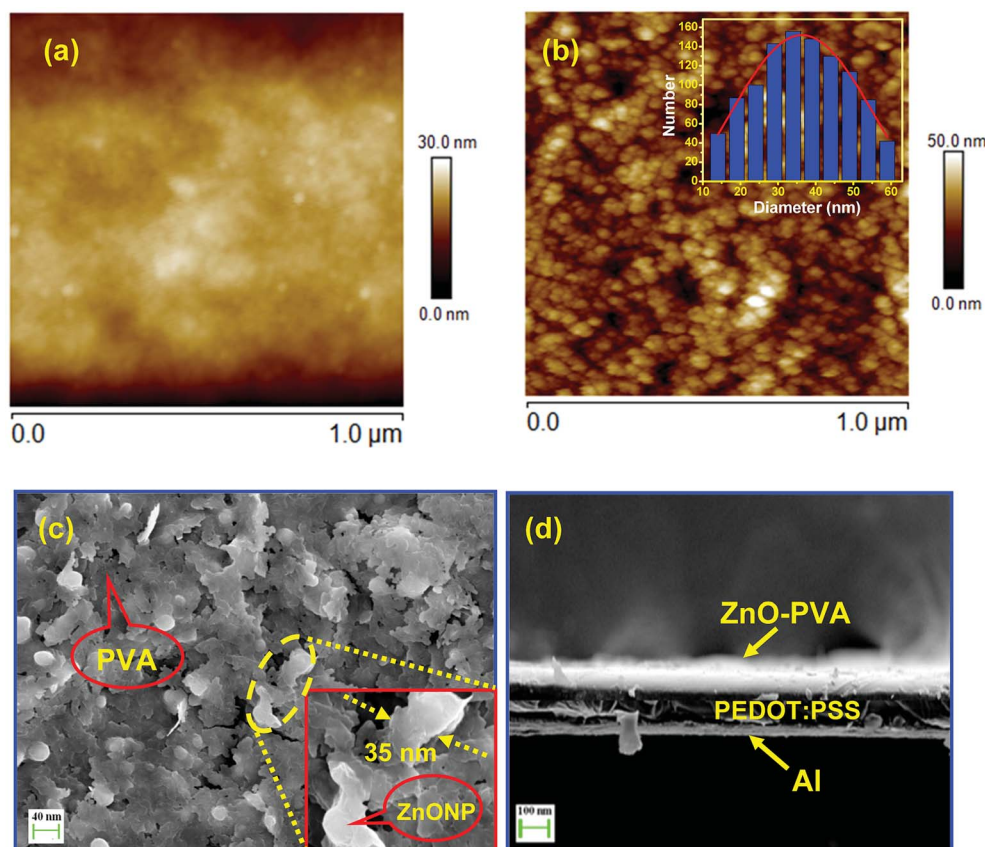


Fig. 1 Plane view of AFM surface topography of (a) pristine PEDOT:PSS films. (b) ZnO–PVA nanocomposite/PEDOT:PSS heterostructure deposited on flexible Al coated PET substrates. The particle size distribution is plotted at the inset. (c) Plane view SEM image of ZnO–PVA nanocomposite deposited on the surface of PEDOT:PSS films. (d) The cross sectional SEM image of ZnO–PVA nanocomposite/PEDOT:PSS/Al heterostructure sample.

of stoichiometrically pure ZnO in PVA matrix. The additional elements Zn, O and C arise from carbon coated copper grids and PVA polymer.

3.2 Optical characterization

Fig. 2(b) shows the UV-visible absorption spectra of ZnO–PVA nanocomposite films with and without attachment of PEDOT:PSS in the range of 300–800 nm. The optical band gap (E_g) of ZnO–PVA nanocomposite has been calculated using Tauc's formula.³⁶

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad (1)$$

where α is the absorption coefficient, $h\nu$ is the incident photon energy and A is a constant. Inset of Fig. 2(b) represents $(\alpha h\nu)^2$ vs. $h\nu$ plot for both samples. The optical band gap of ZnO–PVA nanocomposite and absorption edge of ZnO–PVA nanocomposite/PEDOT:PSS have been calculated by extrapolation at the linear region of $(\alpha h\nu)^2$ vs. $h\nu$ plot to the energy axis.

The pristine ZnO–PVA nanocomposite shows strong absorption in the UV region of wavelength threshold at 387 nm, corresponding to the energy band gap of 3.2 eV. Interestingly, the absorption edge has been slightly shifted to higher wavelength for ZnO–PVA nanocomposite deposited on PEDOT:PSS films (~ 3.15 eV), which is attributed to the strengthened photo-absorption in visible region. Moreover, the additional peak at 503 nm has been observed, which is attributed to the absorption edge of ZnO–PVA nanocomposite/PEDOT:PSS.³⁷ Fig. 2(c) shows the XRD spectra of the PEDOT:PSS film, ZnO–PVA nanocomposite films and ZnO–PVA nanocomposite/PEDOT:PSS heterostructure films deposited on Al coated flexible PET substrates. The XRD result clearly indicates that both ZnO–PVA nanocomposites and ZnO–PVA nanocomposite/PEDOT:PSS are highly crystalline. The strongest diffraction peaks observed at $2\theta = 31.72^\circ$, 34.40° , 36.21° , 47.49° , 56.52° , 62.80° , 67.83° , and 68.97° corresponding to the lattice planes (100), (002), (101), (102), (110), (103), (112), and (201) respectively, are attributed to the hexagonal wurtzite structure of ZnO.



Fig. 2 (a) Energy dispersive X-ray spectrum (EDX) of ZnO nanoparticles embedded in PVA matrix. (b) UV-visible absorption spectra of ZnO–PVA nanocomposite films and ZnO–PVA nanocomposite/PEDOT:PSS heterostructure films. $(\alpha h\nu)^2$ vs. $h\nu$ plot for ZnO–PVA nanocomposite and ZnO–PVA/PEDOT:PSS heterostructure (inset). (c) X-ray diffraction spectra of PEDOT:PSS, ZnO–PVA nanocomposite and ZnO–PVA nanocomposite/PEDOT:PSS heterostructure grown on PET substrates.



The data is in well agreement with the JCPDS card number 36-1451.³⁸ Interestingly, ZnO-PVA nanocomposites/PEDOT:PSS exhibits the same diffraction patterns with ZnO-PVA nanocomposites, and the additional diffraction peaks at 26° and 52.9° have been observed due to the diffraction from PET substrate.³⁹ However, no diffraction peak can be observed for the pure PEDOT:PSS film except two diffraction peaks at 26° and 52.9° due to the diffraction from PET substrate,³⁹ demonstrating its poor crystalline structure.

3.3 Electrical characterization

To study the resistive switching characteristics of ZnO-PVA nanocomposites [concentration ratio (ZnO : PVA) of 10 : 1]/conducting polymer heterostructure, the following three samples have been fabricated. The samples are (i) Al/PEDOT:PSS/Al/flexible PET substrate (denoted as S1), (ii) Al/ZnO-PVA/Al/flexible PET substrate (denoted as S2) and (iii) Al/ZnO-PVA/PEDOT:PSS/Al/flexible PET substrate (denoted as S3). In electrical measurements, Al top electrodes (TE) were connected to negative ('-') and Al bottom electrodes (BE) were connected to positive ('+') terminal to the source meter. Fig. 3(a) shows the schematic diagram of the S3 memory device and molecular structure of PEDOT:PSS film. Fig. 3(b) shows the current-voltage (*I*-*V*) switching characteristics of the S3 device.

The external electrical stimulation is supplied to the device in the form of an applied voltage in a sequence of $0\text{ V} \rightarrow +4\text{ V} \rightarrow 0\text{ V} \rightarrow -4\text{ V} \rightarrow 0\text{ V}$, with a current compliance of $5.1 \times 10^{-2}\text{ A}$ to prevent the permanent dielectric breakdown of the device. The high-conductivity state (ON-state) was achieved by applying a forward voltage sweep on the device. With increasing positive voltage, the current starts increasing and jumps suddenly at $+3.6\text{ V}$, indicating the switching of the device from low conductivity state (OFF-state) to high-conductivity state (ON-state). This switching process from OFF state to ON state is referred to as the "writing" process, and which is known as the SET process. The ON state will remain in that state and will not return to the OFF state even after turning off the power supply (read process). The high conducting state (ON state) process is maintained from $+4\text{ V}$ to -4 V , while reverse sweeping. Subsequently, the ON state switches to a low conducting state (OFF state) at a voltage of -3.6 V , as can be seen in the reverse bias voltage. This transition from ON state to OFF state is equivalent to the 'erasing' process in a digital memory cell,⁴⁰ which is also known as the RESET process. The low conductivity state (OFF-state) of the device can be read and reprogrammed to the high-conductivity state (ON-state) in the subsequent positive sweep, as a result, completing the "write \rightarrow read \rightarrow erase \rightarrow read \rightarrow rewrite" cycle for a non-volatile rewritable memory device.⁴¹ It is observed that, the existence of two conducting



Fig. 3 (a) Schematic diagram of the S3 memory device and molecular structure of PEDOT:PSS films. Current-voltage (*I*-*V*) switching characteristics of the (b) S3 memory device, (c) S1 device and (d) S2 device.

states, *viz.*, low conductivity state (OFF state) and high conductivity state (ON state), exhibiting bistable behaviour. The state of the device was maintained even after removal of the applied bias, indicating the non-volatile memory. It is also seen that, the reversible resistance switching between low conductivity state (OFF state) and high conductivity state (ON state) promises to be used in the rewritable data storage system. Hence, non-volatile bistable memory was demonstrated. Such write or erase processes have been investigated cyclically for 10 times, and no significant changes were observed in the SET and RESET voltage. The ratio ($I_{\text{ON}}/I_{\text{OFF}}$) of the current achieved between the ON and OFF states is about 3×10^5 in magnitude at a reading voltage of 1 V as shown in Fig. 3(b).

For comparison, the two samples S1 and S2 have been fabricated and measured. The electrical performances were inferior as compared to the S3 device, as shown in Fig. 3(c) and (d). It is observed that, the S1 device has no resistivity switching even at a higher operating voltage as shown in Fig. 3(c). In Fig. 3(d), the S2 device shows resistivity switching behaviour at a high operating voltage. But, the performance of the S3 device is significantly improved over the S2 device. The enhancement of the S3 device in resistivity switching behaviour is due to the presence of hole transporting PEDOT:PSS polymer with an efficient hole transport from ZnO to PEDOT:PSS, resulting in higher 'ON state/OFF state' current ratio, as shown in Fig. 3(b). Earlier studies have reported that multilevel conductance

behaviour is revealed in the organic based memory devices,^{42,43} particularly, the devices utilizing metal/metal oxide nano-composite as active materials. However, it is suggested from Fig. 3(b) that our S3 device did not show such behaviour since the currents at both ON and OFF state are rather constant. In practical applications, stability of the device performance is one of the most important characteristics of a memory device. The retention characteristics of the S3 device were analyzed for checking the durability. Fig. 4(a) shows the data-retention characteristics of the ON-state and the OFF-state currents as functions of time at room temperature. Firstly, the OFF state current measurement was carried out at 1 V. After that a pulsed positive bias (voltage 4 V and time 2 μs) was applied to change the device to ON state followed by the ON current measurement at a voltage of 1 V. It is seen that, there was no remarkable degradation of the device in both the ON state and OFF states after 32 minutes continuous operation which manifested excellent stability of the device. Furthermore, there is no noticeable degradation in S3 device performance even after 2 weeks after fabrication. The current values of both the ON states and OFF states are 5.1×10^{-2} and 1.7×10^{-7} A, respectively, and the 'ON state/OFF state' ratio is maintained at 3×10^5 , as shown in Fig. 4(a). The excellent stability and retention performances of this device verify the reliability of this sample and demonstrate their potential for application in non-volatile bistable memory device. Moreover, the resistances of OFF state and ON

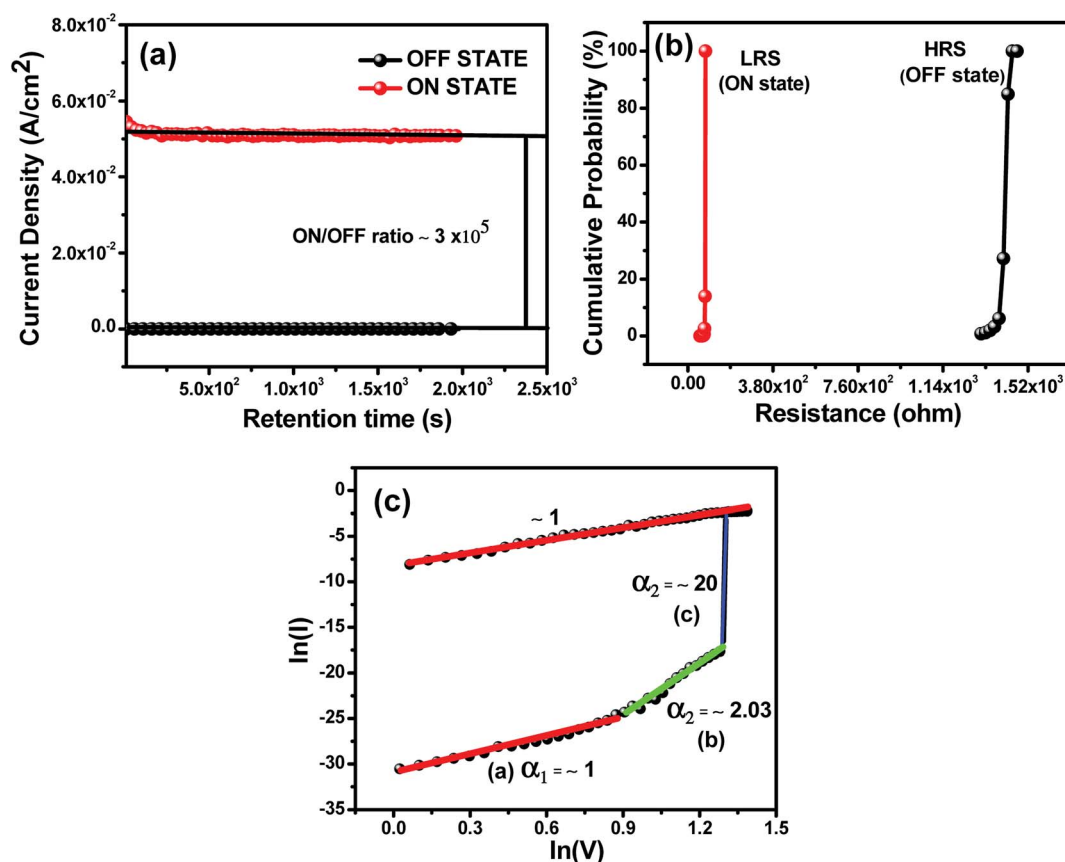


Fig. 4 (a) Retention time measurements of the S3 organic bistable device (OBD) with a read voltage of 1 V. (b) Cumulative probability of S3 memory devices. (c) Linear fitting of the S3 memory device for the I - V curve on a log-log scale showing the SCLC mechanism.



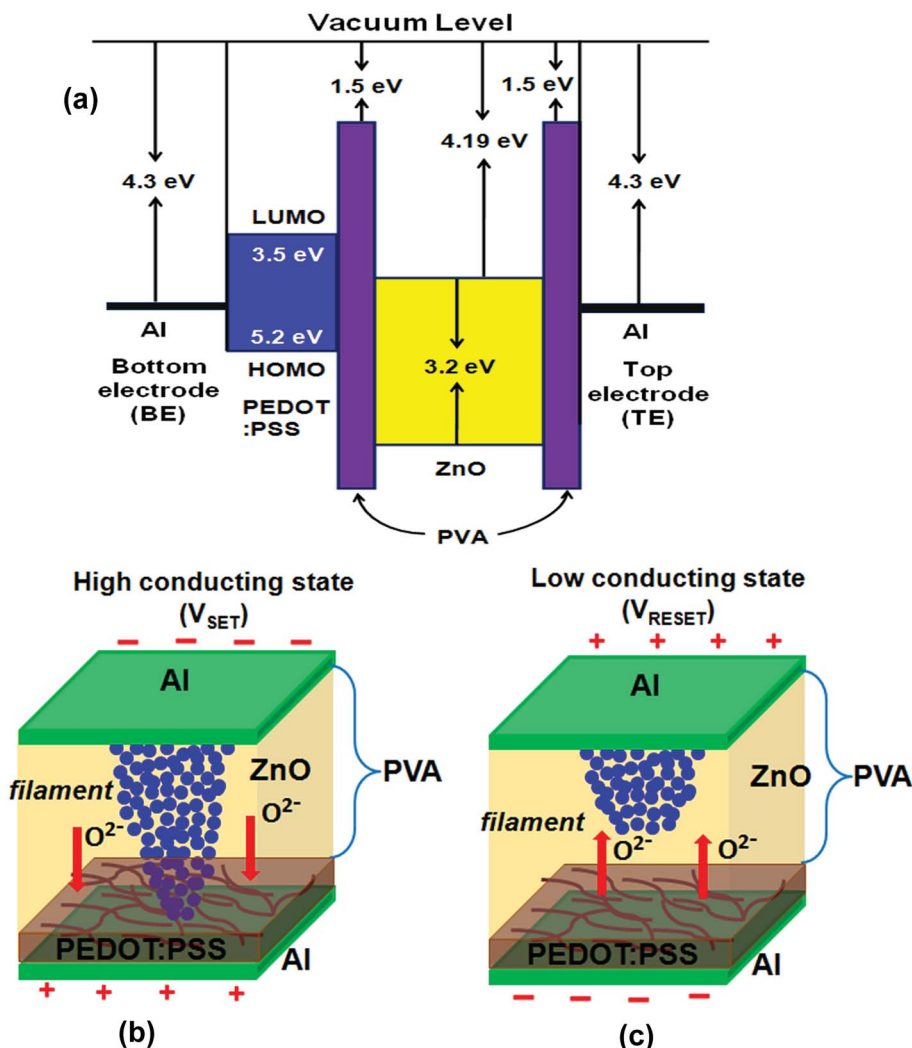


Fig. 5 Schematic diagrams of energy level corresponding to the operating mechanism for the S3 memory device. Schematic diagrams of the electronic structures corresponding to the operating mechanisms for S3 memory device with the (b) high conducting state (SET state) and the (c) low conducting state (RESET state).

state in terms of the cumulative distribution were examined. Fig. 4(b) shows the cumulative probability of switching resistance of the S3 device. The resistance values measured at a read voltage of 1 V is plotted as ON state and OFF state. The distribution of ON state is quite narrow for the device, while the distribution of OFF state is, relatively, broader. The average values of ON state and OFF state are found to be 9 Ω and 1.4 k Ω , respectively, with a high resistance ratio (ON state/OFF state) of more than 3×10^5 . The presented S3 device provides an interesting candidate for high performance non-volatile flexible memory devices.

3.4 Conduction mechanism

To clarify the conduction mechanism of the S3 memory device, the I - V characteristics were re-plotted in a log-log scale as shown in Fig. 4(c). From this plot, it is clearly seen that, the I - V characteristics in OFF-state (low conductivity state) consist of three regions, namely, (a) ohmic region ($I \propto V$) with a slope of $\alpha_1 \sim 1$ at low voltages, (b) Child's square law region ($I \propto V^3$) with

a slope of $\alpha_2 \sim 2.03$ at higher voltages, and (c) steep increase in current region ($I \propto V^m$) with a slope of ~ 20 . Where V is the applied voltages between the two electrodes and m is a positive number. This kind of I - V behavior is in good agreement with typical trap-controlled space charge limited conduction (SCLC) mechanism.⁴⁴ Whereas, the ON-state (high conductivity state) exhibits ohmic conduction behavior with a slope of ~ 1 , which is attributed to the formation of conductive path between the top electrode (TE) and bottom electrode (BE) in the S3 device during the SET process.

Carrier transport in the resistive switching memory device based on ZnO-polymer composites had been explained mostly by SCLC^{45,46} and Fowler-Nordheim (FN) tunneling.⁴⁷ Kim *et al.*⁴⁵ showed that the main conduction in Al/ZnO-PS composites/ITO followed SCLC by fitting the I - V curves. However, the conduction mechanism in the cases of Al/ZnO-PMMA composites/ITO were unclear because it was just predicted as charge trapping without exact fitting of the log-log plot of the I - V curves.¹¹ The conduction mechanism largely depends on the structure and



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