1. Introduction

In recent decades, continuous optimization of computer technologies marking the rapid development of modern information technology has progressively changed people’s lifestyles. Memory is an indispensable carrier of information technology and is regarded as one of the most important technologies in the field of integrated circuits [1]. Semiconductor memory has been widely applied in various fields, such as information technology, social security, aerospace, defense and military [2]. Compared with volatile memory, however, non-volatile memory has great superiority in the field of mobile storage media owing to its ability, to maintain its internal storage properties even after a power failure. With the burgeoning of technologies, various types of new electronic products have emerged in an endless stream. These electronic products also have more stringent requirements for memory performance, such as high reading and writing speeds, high storage density, low power consumption, long life, greater thinness and smaller size [3,4]. The flash memory devices that play significant roles in the current electronic market still suffer from many disadvantages, such as the low operation speed, poor endurance and high write voltage problems. Eventually, miniaturization limits will be a critical issue for flash memory in future application [5]. As a result, most of today’s electronic technology research is focussing on new types of memory devices nowadays. There are many kinds of memory devices based on different mechanisms and materials that are highly likely to replace non-volatile memory, such as resistive random access memory (ReRAM), ferroelectric RAM (FeRAM), magnetic RAM (MRAM), and phase change memory (PCM) [1–6]. Among these new types of memory, resistive switching (RS) memory has been widely studied due to such advantages as its simple preparation process, low energy consumption, predominant memory density, small size, and good compatibility with the conventional CMOS process [7,8]. The ReRAM memory device is a novel non-volatile memory based on the principle of resistance change of thin film materials [9,10]. The ReRAM’s metal/insulator/metal (MIM) structure is composed of a thin film functioning as an insulating layer, with conductive materials as bottom and top electrodes [11,12]. This development has attracted widespread attention in the industry and academia, and many new investigations of resistive memory have been initiated by researchers [13,14]. The RS effect of the insulator layer has been discovered in various kinds of amorphous metal oxides, such as ZnO, HfO₂, TiO₂, MgO, Al₂O₃, and Y₂O₃ [15–19]; and in amorphous perovskite and layered perovskite oxides such as YCrO₃, Pr₀.67Sr₀.33MnO₃, Bi₃.15Bd₀.85Ti₂O₉, SrTiO₃, and Nb-doped SrTiO₃ [20–26], etc. Among these, the amorphous strontium titanate-based memory structure uses the following electrodes: Pt, Ti, and indium tin oxide (ITO) [23–26]. These form Pt/amorphous-SrTiO₃ (a-STO)/Pt [23], Pt/Ti/a-STO/Pt [24], Pt/Ti/a-Nb:STO/Pt [25] and ITO/Ti₂O₃/a-STO/ITO [26] memory cells, respectively.

The electrode affects the resistive switching characteristics of memristor devices, and memristors with different structures are formed using different electrodes and
offering different resistance characteristics [27]. The resistivity characteristics of amorphous strontium titanate memory with fluorine doped tin oxide (FTO) and Au electrodes have not yet been reported. In this work, FTO was used as the electrode; we report here the RS characteristic of an Au/amorphous SrTiO$_3$/FTO/Glass memristor fabricated by the sol-gel method. The RS mechanism is also discussed.

2. Experimental

In this work, amorphous SrTiO$_3$ (abbreviation a-STO) thin film was prepared by the sol-gel method and coating process [28]. Sr(NO$_3$)$_2$ and C$_{16}$H$_{32}$O$_4$Ti were selected as raw materials. Ethylene glycol ((CH$_2$OH)$_3$) and 2,4-Pentanediol were used as organic solvents for Sr(NO$_3$)$_2$ and C$_{16}$H$_{32}$O$_4$Ti, respectively. First, Sr(NO$_3$)$_2$ raw material was dissolved in (CH$_2$OH)$_3$ at 60°C under continuous stirring until it was completely dissolved. C$_{16}$H$_{32}$O$_4$Ti was dissolved in 2,4-Pentanediol at room temperature. In order to ensure that the solute was distributed completely in the solvent, the reaction flask and the experiment environment was kept clean and dry. Secondly, these two solutions were mixed under continuous stirring at 60°C for 2 hours. Stirring of the mixed solution was then continued. Finally, 2,4-Pentanediol solvent was used to adjust the final mixed solution to 0.25 mol/L. No deposition was added to the final mixed solution after it was left standing for 3 days, enabling it to be used for fabrication. Prior to depositing the film, the precursor solution was filtered with filter paper to avoid particulate contamination. The precursor solution was then deposited smoothly on a commercially available FTO-coated glass substrate. The solution spreads evenly on FTO/glass substrates under 3000 rpm speed rotation. Then coated wet film was then placed on a stable heating platform to promote thermal decomposition. The first process of thermal decomposition was conducted at about 300°C for 15 min. The above steps were duplicated three times to achieve a film thickness of about 200 nm. Finally, the film was annealed at 400°C for 20 min in the air by the RTP-1000D4 Rapid Thermal Annealing method (RTA, Hefei Kejing Materials Technology Co., LTD, China) at a heating rate of 3 °C/s.

A cross-sectional image of a-STO thin film was observed using a scanning electron microscope (SEM, Hitachi S-3400N-II). X-ray photoelectron spectroscopy (XPS, Escalab 250Xi) was applied to analyze the surface composition, chemical states and precise positioning of the thin film with a beam spot diameter of 650 mm. The room temperature current-voltage properties of the Au/a-STO/FTO device were characterized by a two-probe method using a Keithley 2400 programmable electrometer (Tektronix Company, USA).

3. Results and discussion

3.1. Microstructure

Figure 1(a) displays a schematic illustration of Au/a-STO/FTO heterostructure devices for measurement. Glass was selected as the substrate, and FTO and Au were used for the bottom and top electrodes, respectively. An SEM image of a cross-section of the a-STO thin film is shown in Figure 1(b). The thickness of the a-STO thin film can be seen to be about 200 nm. But no obvious grain can be observed in the film, which has a different morphology from FTO layers with columnar grains. In addition, the a-STO film shows a smooth appearance with no holes or cracks, and the thickness of the film is about 200 nm. It is indicated that the connector between the top and bottom electrode layers is well congested with a compact microstructure. In addition, the GIXRD pattern of STO/FTO/Glass with the intensity increased 10 times and the XRD pattern of FTO/Glass films are shown in Fig. S. The XRD profile of STO/FTO/Glass shows a wide-peaked pattern at around 20 = 10–35°, indicating that STO film is amorphous. It can be observed; moreover, that the three main peaks at (110), (200) and (211) appear in the XRD pattern of STO film, implying a budding polycrystalline perovskite structure in the STO film. These three weak peaks and the clear wide peak at around 20 = 10–35°.
demonstrate that an amorphous structure is dominant in the STO film. In a previous study, it was found that SrTiO$_3$ film retained amorphous sections when the annealing temperature was kept to 700°C [29,30]. In this work, the annealing temperature is 400°C, which is not high enough to promote good SrTiO$_3$ crystallization. The crystallization of the STO film depends on the high-temperature annealing process of RTA.

3.2. XPS analysis

The accurate composition and chemical state of α-STO were studied by XPS. The atomic ratio of Sr/Ti was measured as 1.002, which is exactly the same as the theoretical stoichiometric value of SrTiO$_3$. To investigate the valence states and precise positions of the C 1s, O 1s, Ti 2p and Sr 3d electronic levels in the α-STO thin film, a narrow scan spectrum was fitted using the Advantage data analysis system, as shown in Figure 2. Figure 2(a) clearly shows that the C 1s peak at 284.6 eV was used as a standard to correct the binding energy of the XPS spectrum [31]. There is also a weak peak that can be attributed to C-O bonding at 286.0 eV, which is considered to synthesis by the air-atmosphere annealing process [32]. In Figure 2(b), only two peaks are observed in the XPS spectrum related to Sr 3d. And the spin-orbit splitting between the Sr 3d$_{3/2}$ and the Sr 3d$_{5/2}$ peaks located at 134.9 and 133.25 eV is 1.65 eV, as expected [33]. Analysis of the value of the binding energy of Sr 3d shows that Sr ions have a chemical state of $2^+$. The Ti 2p spectrum (in Figure 2(c)) also presents a doublet structure. Ti 2p$_{1/2}$ and Ti 2p$_{3/2}$ are clearly separated at 463.85 and 458.30 eV, respectively. The spin-orbit splitting between them is 5.55 eV [31,32]. The valence of Ti ions is 4+, which is obtained from binding energy. As shown in Figure 2(d), the fitted O 1s narrow-scan spectrum is also a doublet structure. The O 1s spectra on the film surface can be decomposed into low binding energy (O$_{LBE}$) and high binding energy (O$_{HBE}$) at 529.75 and 531.63 eV, respectively. The O$_{LBE}$ peak and the O$_{HBE}$ peak are caused by oxide and hydroxide/absorbed oxygen [31–33], respectively.

3.3. Resistance switching characteristics

$I$-$V$ curves were measured using a two-point technique with the bottom and top Au electrodes as contacts on FTO and α-STO/FTO with a junction area of 0.05 mm$^2$, as depicted in Figure 1(a). As shown in Figure 3(a), the voltage sweep as a maximum negative voltage ($-2$ V) → 0 → maximum positive voltage (+3 V). The current changes sharply near a negative voltage of $-1.8$ V and a forward voltage of $+2.1$ V, while the current tends to be stable in the $-1.8$ V to $+2.1$ V range. The corresponding

Figure 2. XPS survey spectra of an α-STO thin film. The fitted narrow-scan spectra of (a) C 1s, (b) Sr 3d, (c) Ti 2p, and (d) O 1s.
current in the stable range is extremely low. It can be determined from Figure 3 that Au/a-STO/FTO devices display a remarkable diode feature with the open-circuit voltage reaching +2.1 V. And the weak discrepancies between the 1st, 50th and 100th test results indicate that the diode rectification characteristics of the device are fatigued.

Figure 3(b) displays the I-V hysteresis loops with the sweeping direction of the applied voltage (from 0 to 2 V, then from 2 V to −2 V, and finally from −2 to 0). As shown in the 1st test curve, the memory is initially in a high resistance state (HRS) with a slow current increase when operating at a positive voltage from 0 to 1.00 V. The slight increases can be clearly observed from the semilogarithmic of the I-V hysteresis loops (Figure 3(c)). If the operating bias voltage exceeds the threshold voltage of 1.00 V (V_{set}), however, the current increases suddenly from 6.02 × 10^{-5} to 0.0043 A, suggesting that memory device is transformed from HRS to LRS. Furthermore, the current values decrease gradually after the uninterrupted cycling test. In paths 2 (+2 V→0) and 3 (0→−2 V), the LRS is stably maintained when the applied voltage sweeping is reversed. In path 4, when the operating bias voltage is over the threshold voltage of −0.95 V (V_{reset}), the current sharply decreases from 0.01 to 7.98 × 10^{-5} A. It is worth noting that the second RS from LRS to HRS is as violent as the first switch. In the 50th cycle, the first transition of the resistance state from LRS to HRS takes place at 1.05 V, which is higher than in the 1st cycle. But for the 100th cycle, there is no obvious transition of the resistance state in the positive voltage range, while the resistance state mode is similar for the 1st and 50th cycles in the negative voltage range. To analyze the switching behavior, the ratio of off-state and on-state (R_{off}/R_{on}) was calculated from the positive voltage part of the 1st test results. It was found that the value of R_{off}/R_{on} is about 10^{2} in the 0 V→−1.00 V range. The ratio of R_{off}/R_{on} in the first test results is close to that in the fiftieth results, moreover, which means the effect of RS is greater endurance and retention characteristics.

The statistical distributions of the V_{set} and V_{reset} and R_{on} and R_{off} were measured at 100 cycles to clarify the uniformity of the device. The standard deviation (Δ), average (μ) and coefficient of variation (Δ/μ) of V_{set} and V_{reset} and R_{on} and R_{off} are shown in Table 1. As displayed in Table 1, the Δ/μ of V_{set} and V_{reset} and R_{on} and R_{off} are 0.1769, 0.2327, 0.1662 and 0.3969, respectively. To further analyze the stability of RS effect in the a-STO film, the Weibull distributions of V_{set} and V_{reset} and R_{on} and R_{off} were studied, and the results are shown in Figure 4. The Weibull distribution is expressed as follows [34,35]:

![Figure 3](image_url)

**Figure 3.** Resistive switching behaviors of Au/a-STO/FTO/Glass devices. (a) I-V curves measured for Au/a-STO/FTO/Glass in two opposite polarization states. (b) I-V hysteresis loops measured for multiple cycles. (c) An I-V hysteresis loop plotted on a semilogarithmic scale. (d) The R_{off}/R_{on} ratio for the first I-V hysteresis loops with positive applied voltage.
where $F$ is the cumulative probability, $x$ is the scale factor, the parameter $x_{0.63}$ is the scale factor which is the value of the statistical variable at $F \approx 63\%$, and $\beta$ is the Weibull slope representing the statistical dispersion. The straight-fitting line reveals that the scale factor distributions are in accordance with the Weibull mode, and the values for $x_{0.63}$ and $\beta$ are given by the Weibull plots and their fitting lines. All the parameters of standard Weibull distribution for $V_{\text{set}}$ and $V_{\text{reset}}$ and $R_{\text{on}}$ and $R_{\text{off}}$ are displayed in Table 1, with the $\beta$ found to be 5.5175, 4.0237, 6.6758 and 15.4641, respectively. Higher values for $\beta$ in the Weibull distribution and lower values for $\Delta/\mu$ in the normal distribution indicate the stability and uniformity of the RS properties in the $\alpha$-STO film [35–37].

### Table 1. Distributions of the switching voltages ($V_{\text{set}}$ and $V_{\text{reset}}$) and resistance states ($R_{\text{on}}$ and $R_{\text{off}}$).

| Parameters | $V_{\text{set}}$ | $V_{\text{reset}}$ | $R_{\text{on}}$ | $R_{\text{off}}$ |
|------------|------------------|-------------------|----------------|----------------|
| $\Delta$   | 0.2022 V         | 0.2888 V          | 62.95 $\Omega$ | 2312.49 $\Omega$ |
| $\mu$      | 1.1429 V         | -1.2409 V         | 158.61 $\Omega$ | 13915.14 $\Omega$ |
| $\Delta/\mu$ | 0.1769          | 0.2327            | 0.3969 $\Omega$ | 0.1662 $\Omega$ |
| $\beta$    | 5.5175           | 4.0237            | 15.4641 $\Omega$ | 6.6758 $\Omega$ |
| $x_{0.63}$ | 1.20             | 1.05              | 151.6995 $\Omega$ | 15322.38 $\Omega$ |

### 3.4. Conduction mechanism

Figure 5 shows the $I$-$V$ characteristic curve of Au/$\alpha$-STO/FTO devices. The related fitting of HRS and LRS in the $0\rightarrow+2$ V$\rightarrow0$ range is also drafted, and the plots can be well fitted by linear segments with different slopes. When the voltage was lower than the 1.00 V ($V_{\text{set}}$) in the 1st test of Au/$\alpha$-STO/FTO devices in Figure 5(a), the slope was 1.04, approximating 1 and indicating that the initial HRS state is Ohmic conduction. After this HRS state, the slope of the logarithmic $I$-$V$ curve becomes 1.86, submitting to Child’s Law (Eq. 3). The current then increases steeply to the LRS state, and the slope value is 1.10, showing an Ohmic conduction mechanism [38,39]. In Figure 5(b), a similar phenomenon can also be observed in the 50th cycling test results, where the log|I| vs. log|V| curve in the HRS state is initially composed of Ohmic conduction ($I \sim V^{0.99}$) and a higher slope segment ($I \sim V^{1.28}$) and then shows Ohmic conduction ($I \sim V^{1.10}$) in the LRS state. It is well known that there are two leakage current mechanisms, namely Ohmic and space-charge-limited conduction (SCLC, Child’s Law) [40–42]. The $I$-$V$ characteristics can be expressed as [40,41]:

![Figure 4](image-url)  
**Figure 4.** Weibull plots of the distributions for: (a) $V_{\text{set}}$ and $V_{\text{reset}}$ and (b) $R_{\text{on}}$ and $R_{\text{off}}$.

![Figure 5](image-url)  
**Figure 5.** $I$-$V$ curves plotted as log|I| vs. log|V| with the positive voltage range: (a) 1st test results and (b) The 50th test results.
$$J_{\text{Ohmic}} = qn_0\mu \frac{V}{d} \quad (2)$$

$$J_{\text{SCLC}} = \frac{9}{8} \varepsilon \mu_e \frac{V^2}{d^2} \quad (3)$$

where the parameters $J$, $q$, $V$, $n_0$, $\varepsilon$, $\mu$, and $d$ are the current density, elementary charge, applied voltage, concentration of free charge carriers in thermal equilibrium, static dielectric constant, electron mobility, and thickness of the thin film, respectively.

The slope of $I \sim V$ is 1, indicating Ohmic conduction. While the slope of $I \sim V$ is larger than 1, the current increases sharply with the applied voltage, which is similar to the phenomenon seen in the later HRS region. With increases in the applied voltage, more and more electrons are injected into the insulating layer, leading to a disproportion of the space charge. Consequently, the SCLC mechanism becomes dominant. This same physical conduction mechanism is found in many amorphous films [26,43]. To sum up, HRS in the later stage of the prepared memory is mainly controlled by SCLC, while Ohmic conduction is dominant in the initial HRS and LRS regions.

### 3.5. Filament principle

It is reported that the significant physical conduction mechanisms include conductive filament growth and rupture, charge trapping and release, and electrothermal chemical transformation. The formation of conductive filaments is related, moreover, to oxygen vacancies or metal ions. According to the previous analysis of the RS mechanism, we refer to the oxygen vacancies (OVs)-dependent filament mode to explain the RS mechanism in Au/a-STO/FTO memory devices [44–47]. As displayed in Figure 6, the small dots represent oxygen atoms in the filament model. Initially, OVs are randomly dispersed in the $\alpha$-STO representing the front of the HRS range. As the applied voltage increases, filaments are formed by the composed OVs after the setting process, and the device is transferred from HRS to LRS. Then, Ohmic conduction plays a dominant role in the LRS range. The thermal effects due to electronic motion and memory switching from LRS to HRS then eliminate the oxygen vacancies, causing filament breakdown. The primary conduction mechanism of HRS is SCLC, indicating that some oxygen defects are still present in the film.

### 4. Conclusions

In summary, the RS effect of amorphous $\alpha$-STO-based memristive devices, which were prepared by the traditional chemical solution deposition route, has been demonstrated. The most significant finding is that the largest $R_{\text{off}}/R_{\text{on}}$ ratio of the $\alpha$-STO/FTO heterostructure devices reaches $10^2$. The results for Weibull distribution and normal distribution indicate stable switching voltages ($V_{\text{set}}$ and $V_{\text{reset}}$) and uniform resistance states ($R_{\text{on}}$ and $R_{\text{off}}$) as RS characteristics in $\alpha$-STO films. The conduction mechanism was also investigated, revealing that the Ohmic conduction is dominant in the HRS state, and that the SCLC model dominates the conduction in the second part of HRS. Then, after HRS is transformed to the LRS state, the Ohmic conduction becomes dominant again. A reasonable filament theory of formation and rupture of oxygen vacancies was established, moreover, to explain the transitions of the HRS and LRS states. This study provides a memristive device with excellent performance and low-temperature preparation which can promote applications in the ReRAM field.

### Acknowledgments

The authors thank the Guangdong University of Technology Analysis and Test Center for use of X-ray photoelectron spectroscopy. We also thank Dr. Tiedong Cheng for his measurement program.

### Disclosure statement

No potential conflict of interest was reported by the authors.

### Funding

This work was supported by the National Natural Science Foundation of China under Grants Nos. 11574057, 11574058 and 51604087; the Guangdong Provincial Natural Science Foundation of China under Grant No. 2016A030313718; and the Science and Technology Program of Guangdong Province of China under Grants Nos. 2016A010104018, and 2017A010104022.

---

**Figure 6.** Model of an oxygen vacancy-related filament.
References

[1] Chang TC, Chang KC, Tsai TM, et al. Raistance random access memory. Mater Today. 2016;19(5):254–264.

[2] Pan F, Chen C, Wang ZS, et al. Nonvolatile resistive switching memories: characteristics mechanisms and challenges. Prog Nat Sci Mater Int. 2010;20:1–15.

[3] Kolar J, Macak JM, Terabe K, et al. Down-scaling of resistive switching to nano scale using porous anodic alumina membranes. J Mater Chem C. 2014;2:349–355.

[4] Acharyya D, Hazra A, Chattarcharya P. A journey towards reliability improvement of TiO2 based resistive random access memory: A review. Microelectron Reliab. 2014;54(3):541–560.

[5] Pan F, Gao S, Chen C, et al. Recent progress in resistive random access memories: materials, switching mechanisms, and performance. Mater Sci Eng R. 2014;83:1–59.

[6] Islam R, Li HT, Chen PY, et al. Device and materials requirements for neuromorphic computing. J Phys D Appl Phys. 2019;52(11):113001.

[7] Zhu LG, Zhou J, Guo ZL, et al. An overview of materials issues in resistive random access memory. J Materiomics. 2015;1(4):285–295.

[8] Sharma Y, Pavuny SP, Fachini E, et al. Nonpolar resistive memory switching with all four possible resistive switching modes in amorphous LaHoO3 thin films. J Appl Phys. 2015;118(9):094501.

[9] Nishi Y, Sasakura H, Kimoto T. Conductance fluctuations in NiO-based resistive switching memory. J Appl Phys. 2018;124(15):152134.

[10] Zhang Q, Xia GG, Li LB, et al. High-performance Zinc-Tin-Oxide thin film transistors based environment friendly solution process. Curr Appl Phys. 2019;19(2):174–181.

[11] Strukov DB, Snider GS, Stewart DR, et al. The missing memristor found. Nature. 2008;453:80–83.

[12] Del Valle J, Ramirez JG, Rozenberg MJ, et al. Challenges in materials and devices for resistive-switching-based neuromorphic computing. J Appl Phys. 2018;124(21):211101.

[13] Samitsu A, Tomioka Y, Kuyahara H, et al. Current switching of resistive states in magnetoresistive manganese. Nature. 1997;388:50–52.

[14] Fadel M. Switching phenomenon in evaporated Se-Ge-A thin films of amorphous chalcogenide glass. Vacuum. 1993;44(8):851–855.

[15] Cheng TD, Rao JJ, Tang X, et al. Analog memristive characteristics and conditioned reflex study based on Au/ZnO/ITO devices. Electronics. 2018;7(8):151.

[16] Shang J, Xue WH, Ji ZH, et al. Highly flexible resistive switching memory based on amorphous-nanocrystalline hafnium oxide films. Nanoscale. 2017;9(21):7037–7046.

[17] Yu YM, Yang F, Mao SS, et al. Effect of anodic oxidation time on resistive switching memory behavior based on amorphous TiO2 thin films device. Chem Phys Lett. 2018;706(16):477–482.

[18] Quan XT, Zhu HC, Cai HT, et al. Resistive switching behavior in amorphous aluminum oxide film grown by chemical vapor deposition. Chin Phys Lett. 2014;31(7):078101.

[19] Das M, Kumar A, Mandal B, et al. Impact of schottky junctions in the transformation of switching modes in amorphous Y2O3-based memristive system. J Phys D Appl Phys. 2018;51(31):315102.

[20] Sharma Y, Misra P, Katjyar RS. Unipolar resistive switching behavior of amorphous YCrO3 films for nonvolatile memory applications. J Appl Phys. 2014;116(8):084505.

[21] Zhang T, Bai Y, Jia CH, et al. Interface-related switching behaviors of amorphous Pr0.67Sr0.33MnO3-based switching memory cells. Chin Phys B. 2012;21(10):107304.

[22] Song HJ, Yan WZ, Zhong XL, et al. Total ionizing dose effects on Ag/amorphous Bi1.15Nd0.85TiO2/Pt resistive switching memory. Mater Chem Phys. 2018;219:340–346.

[23] Yan XB, Yin J, Liu ZG, et al. Studies on the reset power needed for the unipolar resistive switching in amorphous SrTiO3.5 films induced by electrical pulse. Phys Lett A. 2011;375(41):3599–3603.

[24] Nilii H, Walla S, Balendhuran S, et al. Nanoscale resistive switching in amorphous perovskite oxide (α-SrTiO3) memristors. Adv Funct Mater. 2014;24:6741–6750.

[25] Nili H, Walla S, Kandjani AE, et al. Donor-induced performance tuning of amorphous SrTiO3 memristive nanodevices: multistate resistive switching and mechanical tunability. Adv Funct Mater. 2015;25:3172–3182.

[26] Ahmed T, Walla S, Kim J, et al. Transparent amorphous strontium titanate resistive memories with transient photo-response. Nanoscale. 2017;9(38):14690–147029.

[27] Zhang TF, Tang XG, Liu QX, et al. Electrode effect regulated resistance switching and selector characteristics in Nb doped SrTiO3 crystal for potential cross-point memory applications. J Alloys Compd. 2018;730:516–520.

[28] Wang YG, Tang XG, Liu QX, et al. Ferroelectric and ferromagnetic properties of SrTiO3Fe2O3 thin films. Solid State Commun. 2015;202:24–27.

[29] Zanetti SM, Leite ER, Longo E, et al. Cracks developed during SrTiO3 thin-film preparation from polymeric precursors. Appl Organomet Chem. 1999;13:373–382.

[30] Pontes FM, Lee EJH, Leite ER, et al. High dielectric constant of SrTiO3 thin films prepared by chemical process. J Mater Sci. 2000;35(19):4783–4787.

[31] Psiek B, Szade J, Sotz K. SrTiO3 surface modification upon low energy Ar+ bombardment studied by XPS. Vacuum. 2016;131:14–21.

[32] Jiang LL, Tang XG, Kuang SJ, et al. Surface chemical states of barium zirconate titanate thin films prepared by chemical solution deposition. Appl Surf Sci. 2009;255(21):8913–8916.

[33] Kathalingam A, Kesavan K, Rana A, et al. Analysis of Sn concentration effect on morphological, optical, electrical and photonic properties of spray-coated Sn-doped CdO thin films. Coatings. 2018;8(5):167.

[34] Weibull W, Sweden S. A statistical distribution function of wide applicability. J Appl Mech. 1951;18:293–297.

[35] Wang GM, Long SB, Yu ZA, et al. Impact of program/erase operation on the performances of oxide – based resistive switching memory. Nanoscale Res Lett. 2015;10:39.

[36] Long SB, Lian XJ, Ye TC, et al. Cycle-to cycle intrinsic RESET statistics in HfO2-based unipolar RRAM devices. IEEE Electron Device Lett. 2013;34(5):623–625.

ORCID

Hui Tang http://orcid.org/0000-0002-3354-2522

Xin-Gui Tang http://orcid.org/0000-0001-6429-2098
[37] Frascaroli J, Volpe FG, Brivio S, et al. Effect of Al doping on the retention behavior of HfO$_2$ resistive switching memories. Microelectron Eng. 2015;147:104–107.

[38] Wu SX, Ren LZ, Qing J, et al. Bipolar resistance switching in transparent ITO/LaAlO$_3$/SrTiO$_3$ memristors. ACS Appl Mater Interfaces. 2014;6(11):8575–8579.

[39] Chen GL, Zhang P, Pan LL, et al. Flexible nonvolatile resistive memory devices based on SrTiO$_3$ nanosheets and polyvinylpyrrolidone composites. J Mater Chem C. 2017;5:9799–9805.

[40] Lai YF, Qiu WB, Zeng ZC, et al. Resistive switching of plasma-treated zinc oxide nanowires for resistive random access memory. Nanomaterials. 2016;6(1):16.

[41] Zhou GD, Xiao LH, Zhang SJ, et al. Mechanism for an enhanced resistive switching effect of bilayer NiOx/TiO$_2$ for resistive random access memory. J Alloys Compd. 2017;722:753–759.

[42] Matsuo H, Kitanaka Y, Noguchi Y, et al. Electrical conduction mechanism in BiFeO$_3$-based ferroelectric thin-film capacitors: impact of Mn doping. J Asia Ceram Soc. 2015;3(4):426–431.

[43] Zou LL, Hu W, Xie W, et al. Excellent resistive switching property and physical mechanism of amorphous TiO$_2$ thin films fabricated by a low-temperature photochemical solution deposition method. Appl Surf Sci. 2014;311:697–702.

[44] Ye C, Wu JJ, He G, et al. Physical mechanism and performance factors of metal oxide based resistance switching memory: A review. J Mater Sci Technol. 2016;32(1):1–11.

[45] Larentis S, Cagl C, Nardi F, et al. Filament diffusion model for simulating reset and retention processes in RRAM. Microelectron Eng. 2011;88(7):1119–1123.

[46] Lin KL, Hou TH, Shieh JS, et al. Electrode dependence of filament formation in HfO$_2$ resistive-switching memory. J Appl Phys. 2011;109(8):084104.

[47] Sawa A. Resistive switching in transition metal oxides. Materialstoday. 2008;11(6):28–36.