Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp144-145

Study of Bipolar Multilevel Memristive Mechanism and Characterizations in a Thin FeO_x Transition Layer Device

Guo-Yuan Wu[1], Yao-Feng Chang[1], Li-Wei Feng[1], Chun-Yen Chang[1], and Ting-Chang Chang[2]

[1] National Chiao Tung University, Department of Electronics Engineering & Institute of Electronics, Hsinchu, 300, Taiwan
Phone: +886-3-5712121 Ext. 52981 Email: cycassist@gmail.com
[2] National Sun Yat-Sen University, Department of Physics, Center for Nanoscience & Nanotechnology, Kaohsiung, 804, Taiwan

1. Introduction

In addition to improving storage density by device's architecture, specifically in reduction of the device size and 3D integration, another way to improve storage density is multilevel storage. Multilevel storage, which uses multiple distinguished high resistance states (HRS) and low resistance state (LRS) by controlling external electrical conditions, could be achieved. Although the multilevel resistive switching has been studied for many different materials and simulated in different models [1], its complete mechanism has not yet been investigated by the statistics of electrical characterization.

In this letter, the bipolar multilevel memristive and its electrical characteristics were further demonstrated and investigated in a TiN/SiO_2/FeO_x/Fe structure. Additionally, we analyze the statistics of the electrical results in the structure under different electrical operating conditions, specifically in controlling compliance current and stopped voltage. Understanding the electrical statistics of bipolar multilevel memristor can be useful for developing a possible universally physical and mathematical model.

2. Experimental

The detailed fabrication processes of the thin FeO_x transition layer device were described similarly in our previous study [2]. A TiN(50nm)/SiO_2(~50nm)/Fe(50nm) of metal-insulator-metal structure was deposited on Pt/Ti/SiO_2/Si substrate by DC magnetron sputtering (metal) and plasma enhanced chemical vapor deposition system (insulator), respectively. A square area of TiN with side length of 100 μm was patterned on the SiO_2 films. A rapid thermal annealing treatment at 600 °C for 60 sec was performed in argon ambient. Keithley 4200 semiconductor characterization system is used to measure the *I-V* characteristics 50 cycles per electrical conditions of the fabricated devices. The voltages were applied to the TiN top electrode and the Fe bottom electrode was grounded in 3 samples which always obtained consistent results. Have to mention that an electroforming process was required about 0.13 MV/cm.

3. Results and Discussion

Figure 1(a) and 1(b) show that the continuous bipolar switching behaviors of the TiN/SiO_2/FeO_x/Fe structure with the 600°C-60 sec treated condition under a series of compliance current limitations, between 0.3 mA and 10 mA in set process, and under a series of stopped voltage, between 1.25 V and 2.75 V in a reset process, respectively. It is obviously observed that the resistive state of the thin FeO_x material could be easily tunable by controlling external electric conditions.

Figure 2 shows the statistics of the reset of voltage, current, and power as a function of compliance current. The sudden drop of the reset voltage at a higher compliance current condition was supposed that the reset process is dominated by localization Joule heating [1]. Of note, due to the lower reset current compared to its setup compliance current (the slope of linear fitting is 0.86), the reset process is based on the mobile-ion-assisted recovery by external electric field in electrochemical redox reactions.

Figure 3 shows statistics of the set of voltage, current and power as a function of stopped voltage. Because of the set power saturation phenomena with the increase of stopped voltage values, we proposal a power dissipation model on series resistor, which means that the effective energy for "switchable" filaments is constant, as shown in the insert of Fig. 3. Of note, the constitution of a thin FeO_x transition layer would affect the device's electrical characteristics [2] and performances (we will discuss afterward).

In order to prove our idea, the XPS results in a small size device, after set and reset processes, were examined its Fe_3O_4/Fe_2O_3 ratio composition between HRS and LRS, as shown in Fig. 4. Furthermore, the current transport behaviors at HRS were analyzed and separated into two parts: ohmic behavior at low electrical field and Frenkel–Poole emission at high electrical field, as shown in Fig. 5. Also, the relative permittivity could be extracted as shown in Fig. 6. Theoretically, the values of the relative permittivity for Fe_2O_3, FeO, and Fe_3O_4 are 12, 14.2, and 20, respectively [3]. In other words, the reset process should be separated by two parts in our model: First, the thickness of the "switchable" layer could be changed slightly for 1.25 V and 1.50 V of the stopped voltage because of the effectively Joule heating to rupture the conducting filaments. Second, its composition is changed due to the mobile-ion-assisted recovery by external electric field in electrochemical redox reactions for the higher stopped voltage condition.

4. Conclusions

In conclusion, multilevel memristive mechanism and characterizations of a thin FeO_x transition layer in the TiN/SiO_2/FeO_x/Fe structure was investigated as well as its electrical statistics by controlling the compliance current and stopped voltage.

5. References

[1] U. Russo *et. al.*, IEEE Trans. Electron Devices **56**, (2009) 193.
[2] L. W. Feng *et. al.*, Appl. Phys. Lett. **96**, (2010) 222108.
[3] K. F. Young *et. al.*, J. Phys. Chem. Ref. Data **2**, (1973) 313.

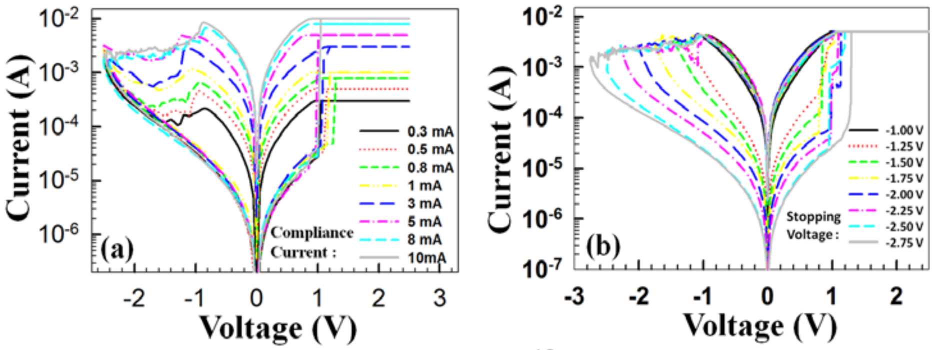

Fig. 1 Bipolar switching behaviors of $TiN/SiO_2/FeO_x/Fe$ structure under (a) a series of compliance current in set process fixed stopped voltage and (b) a series of stopped voltage in reset process fixed compliance current.

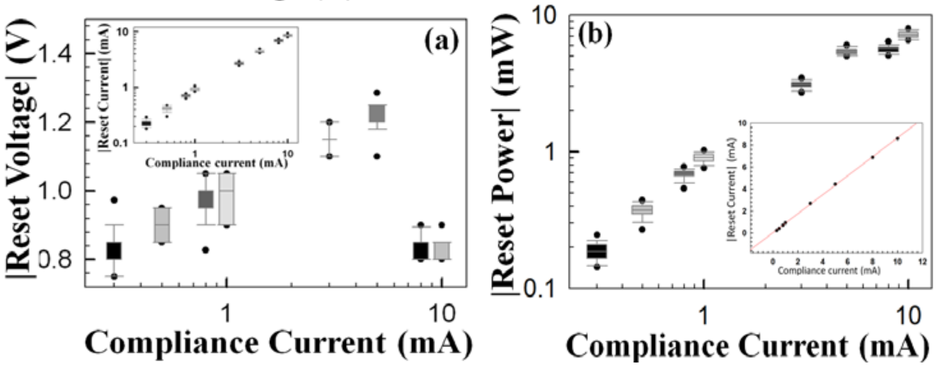

Fig. 2 Statistics plots of (a) reset voltage and current (inset) as a function of compliance current and (b) reset power as a function of compliance current. The red dash fitting line in the inset of (b) shows a linear dependence between two currents.

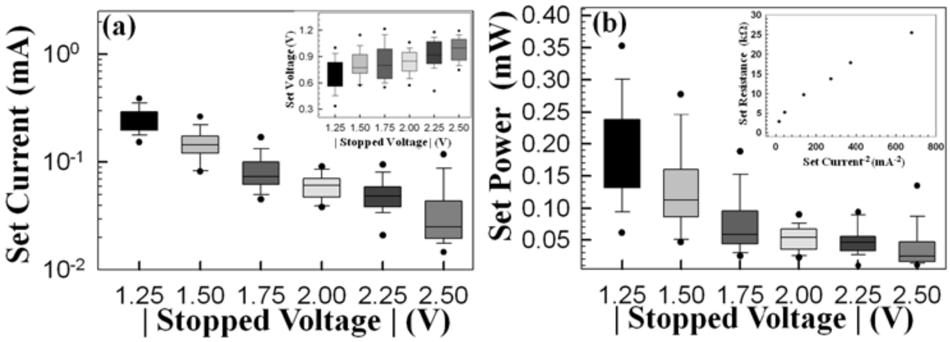

Fig. 3 Statistics plots of (a) set current and voltage (inset) as a function of stopped voltage and (b) set power as a function of stopped voltage. The inset shows the relation between R_{set} and I_{set}^{-2} under a series of stopped voltage.

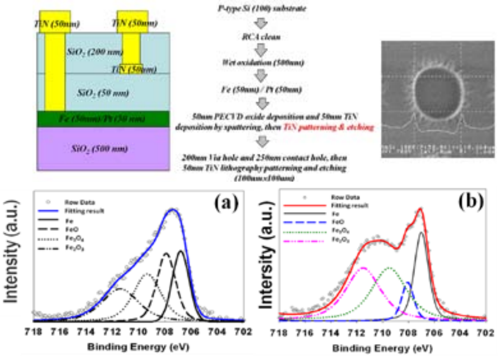

Fig. 4 Illustrations of the small size $TiN/SiO_2/FeO_x/Fe$ structure, its process flows and SEM image. XPS spectra of the FeO_x transition region after (a) a set process (in a LRS) and (b) a reset process (in a HRS) .

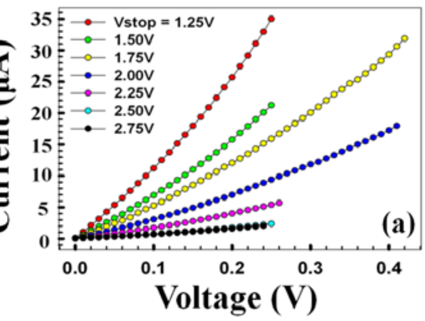
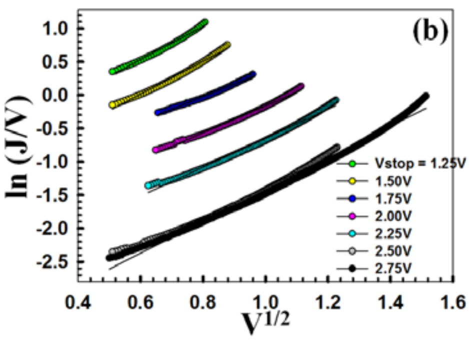

Fig. 5 (a) Linear fitting results for the $TiN/SiO_2/FeO_x/Fe$ structure under a series of stopped voltage in the HRS region. (b) A plot of ln(J/V) vs $V^{1/2}$ under a series of stopped voltage in the HRS region. The linearity criterion of fitting curves is over 99%.

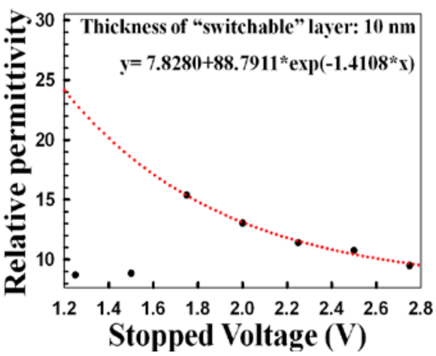

Fig. 6 The relation between relative permittivity and a series of stopped voltage. The red dash fitting line shows an exponential function between 1.75V to 2.75V.