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Understanding the Transition Between Memory and Threshold Switching due to the Compliance Current

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The switching-type transition induced by external parameters, *e.g.*, the thermal conductance and the temperature, has been intensively investigated by using the thermal random circuit breaker (RCB) network model. Recently, some researchers argued that the thermal RCB network model was not able to predict the switching-type transition induced by a new parameter, *i.e.*, the compliance current. However, we demonstrate that the compliance current-induced transition can be explained by using the thermal RCB network model. This work clearly demonstrates that the basic mechanism of unipolar resistance switching is closely related to the formation and the rupture of conducting filaments due to the bias voltage and thermal effects.

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I. INTRODUCTION

Much research has been done on resistance switching phenomena due to potential applications in nonvolatile memories, called resistance random access memory (RRAM) [1–5]. RRAM materials exhibit fast switching speed and nonvolatility. Unipolar memory switching has non-volatile bi-stable states at the reading voltage, which can be controlled by using the magnitude of the bias voltage in one polarity [3]. Unipolar threshold switching has only one stable state at the reading voltage. Little consensus has been achieved on whether unipolar threshold switching is related to unipolar memory switching. We propose that both switching types were closely related and originated from the instability (*e.g.*, the formation and the rupture) of conducting filaments [6]. Interestingly, we found that a transition between memory and threshold switching occurred through a subtle balance between Joule heating and thermal dissipation, which could be controlled by using the thermal conductance (bottom electrode's thickness in the capacitor geometry) [6] and the temperature [7]. We developed the thermal random circuit breaker (RCB) model, which can explain the main features of the transition between memory and threshold switching [7,8].

Recently, some researchers observed a switching-type transition between memory and threshold switching induced by a new external parameter, *i.e.*, the compliance current level (I_c) [9, 10]. They claimed that previous studies including the thermal RCB model were insufficient to explain the transition induced by the compliance current. However, the main physics of the transition in unipolar resistance switching originates from the formation and the rupture of conducting filaments, which can be fully described by the thermal RCB network model [7,8]. In addition, they did not clearly explain previous results on the switching-type transition induced by thermal effects, *e.g.*, thermal conductance [6], temperature [7], and pulse width [11].

In this paper, we present the resistance switching behaviors of Pt/NiO/Pt capacitors for different compliance current levels. In the experiments, we found that a transition between memory and threshold switching could be induced by the compliance current. Based on the thermal RCB model, we were able to understand clearly that the transition induced by the compliance current was related to the balance between connecting and disconnecting the bonds in the percolation network due to thermal effects. We will discuss the role of the compliance current in unipolar memory and threshold switching phenomena.

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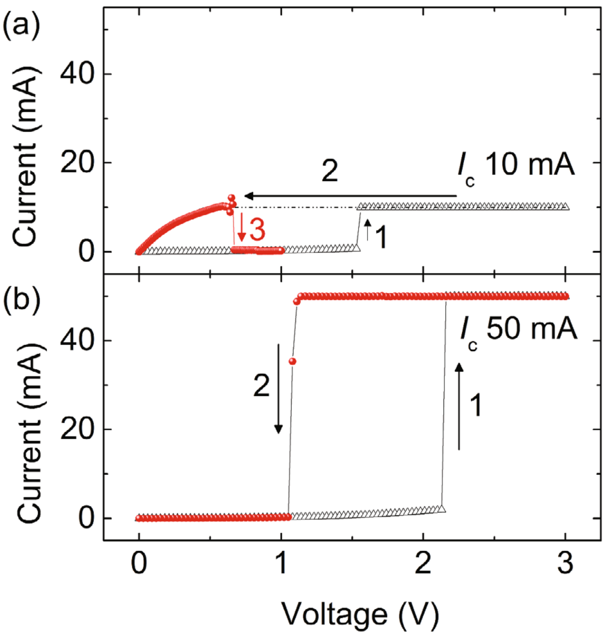

Fig. 1. (Color online) Resistance switching behaviors of a Pt/NiO/Pt capacitor with different compliance currents I_c. (a) A capacitor with small $I_c = 10$ mA shows memory switching behavior. (b) A capacitor with large $I_c = 50$ mA shows threshold switching behavior.

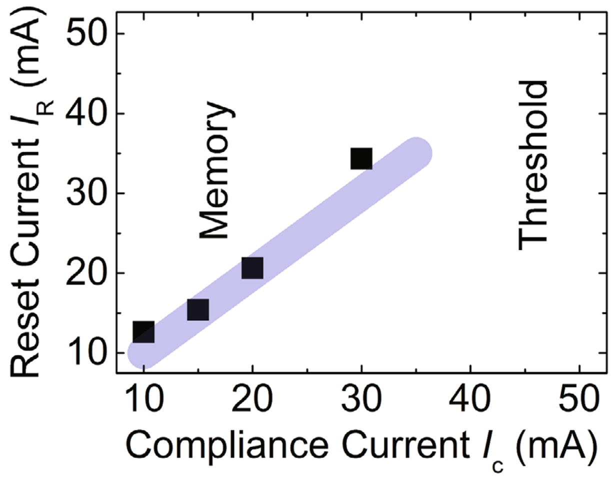

Fig. 2. (Color online) Relationship between the compliance current I_c and the reset current I_R.

II. EXPERIMENTS AND DISCUSSION

We fabricated Pt/NiO/Pt capacitor structures by growing polycrystalline NiO films with optimal conditions for memory switching [6]. Current (I) - voltage (V) measurements were measured with a conventional two-probe measurement system (Agilent 4155C Semiconductor Parameter Analyzer, Agilent Technologies, Santa Clara, CA). In the measurement, the compliance current (I_c) level was controlled to set a limit on the current flow. The thermal random circuit breaker (RCB) network model is a bond percolation model composed of *on* (conducting)- and *off* (insulating)-circuit breakers [7]. We will discuss the details of thermal RCB network model later.

Figure 1(a) shows the memory switching of a Pt/NiO/Pt capacitor with a given I_c, 10 mA. The resistance switching in Fig. 1(a) is unipolar memory switching. When we increased the voltage, the resistance changed to a low resistance state (LRS) at the SET voltage ('1' process in Fig. 1(a)). In this SET process, I_c can prevent total dielectric breakdown and can affect the resistance value of the LRS. When we decreased the voltage from a high voltage value near the SET voltage to zero by using the I_c, the LRS in memory switching became stable, which is denoted by '2' in Fig. 1(a). When we increased the voltage again without the I_c, the resistance state changed to a high resistance state (HRS) at the RESET voltage ('3' process in Fig. 1(a)).

Unipolar threshold switching cannot maintain the LRS when the voltage is decreased to zero even with I_c, as shown in Fig. 1(b). Threshold switching is usually not suitable for a nonvolatile memory device, but it is useful for device integration [12,13]. Figure 1(b) shows the threshold switching in the same Pt/NiO/Pt capacitor with a higher I_c value, 50 mA, than that of memory switching. The transition from memory switching at lower I_c to threshold switching at higher I_c is consistent with the previous report [10]. We found that threshold switching induced by a high I_c is so unstable that in the successive second cycle, it turned into breakdown or memory switching due to the forming of conducting filaments.

Figure 2 shows the correlation between the resistance value of the LRS and the I_c level. A higher I_c can induce a lower resistance value of the LRS and a higher RESET current level. However, the region with I_c above 40 mA does not exhibit a LRS. During the SET process, a higher I_c level allows the Pt/NiO/Pt capacitor to form more conducting filaments.

Next, we performed simulations with the thermal RCB network model. The thermal RCB network model has two simple rules for switching the resistance state of circuit breakers: (i) a voltage-driven process for turning-on operation and (ii) a thermal-driven process for turning-off operation. The thermal effect in the circuit breakers is a balance between Joule heating (*i.e.*, ir^2, where i and r are the local current and local resistance, respectively) due to current flow and thermal dissipation ($-a(T-T_b)$ where a is the thermal conductance of each bond and T_b is the temperature of the thermal bath) through the thermal contact with the thermal bath. When the local temperature of a circuit breaker reaches the threshold temperature, the circuit breaker changes to an off state. If the applied bias voltage is larger than the critical voltage, the circuit breaker changes to an on state. The detailed conditions and procedure for the simulation are

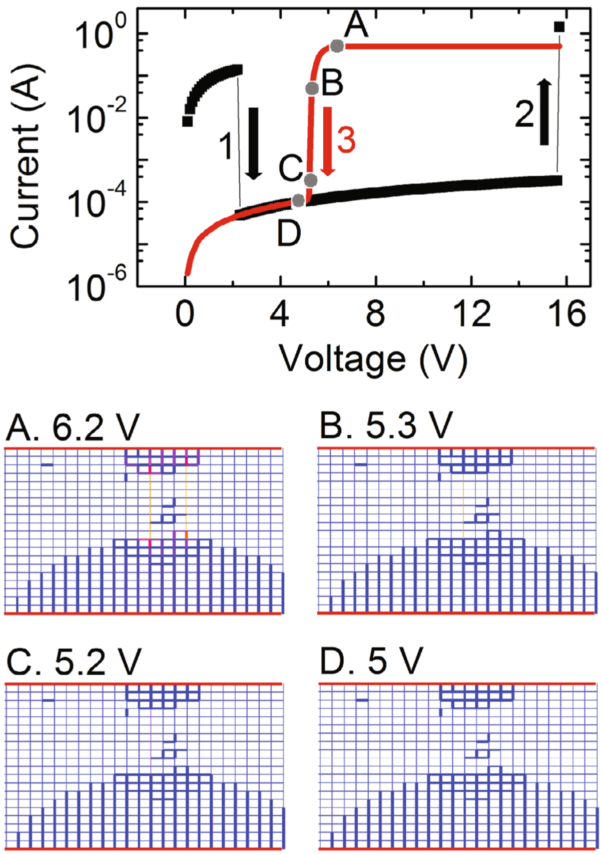

Fig. 3. (Color online) Thermal random circuit breaker (RCB) network model for I-V switching curves.

presented elsewhere [7].

Using the thermal RCB network model, we were able to obtain memory switching behavior in the I-V curve (black line), as shown in Fig. 3. When we increase the voltage from zero, the on-state circuit breakers can be turned off due to Joule heating effect. Then, the conducting paths, especially the hottest bond, are disconnected and the resistance state becomes a HRS from a LRS, the so-called RESET process, indicated of '1' of Fig. 3. We can simulate the SET process ('2' in Fig. 3) by using our thermal RCB network model when we increase the voltage and the local applied bias voltage reaches the critical voltage. We confirmed that after the SET process, the resistance state in the second sweep of the I-V curve is the LRS and that the bi-stable state in memory switching is stable.

To get further insight into the transition between memory and threshold switching, we controlled the Ic level and decreased the voltage gradually after the SET process, as shown in Fig. 3 (red line). Then, we calculated the voltage distribution and subsequent local temperature changes, as demonstrated in Fig. 3 (bottom). We took snapshots of the local resistance states (on- and off-circuit breakers are the thick and the thin lines, respectively) and the local temperature of each bond, represented by the different colors (blue < purple < magenta < yellow), near the threshold temperature. Interestingly, we found an instability of the LRS near 6 V for a high I_c level, denoted by '3' in Fig. 3.

Base on the model simulations, we suggest that the transition is closely related to the rupture of conducting filaments due to a thermal effect. At voltage above 6.5 V, the LRS can be maintained due to the applied bias voltage. When the voltage is decreased to 6.2 V, as shown in Fig. 3, the two hottest bonds (yellow line) reach the threshold temperature and become an off circuit breaker (insulating). Although the bond was insulating, the resistance followed $\exp(\phi/k_BT)$ with an activation energy $\phi = 75.8$ meV [7] and was still lower than that of the HRS due to Joule heating due to the current flow. When the last hottest bond was cooled down to about 5.2 V, the resistance state abruptly changed to the HRS, as shown in Fig. 3. Threshold switching is mainly governed by a thermally-induced rupturing process. The switching-type transitions (controlling thermal conductance, temperature, and compliance current) from our group, as well as those from previous reports (compliance current, pulse width control) by other groups, can be explained by using the thermal RCB network model.

III. CONCLUSION

In conclusion, we investigated the switching-type transition between memory and threshold switching by using thermal random circuit breaker (RCB) network model. By increasing the compliance current, we experimentally observed a switching-type transition from memory to threshold switching. The thermal RCB network model was able to demonstrate a switching-type transition by controlling the compliance current. This clearly indicates that the main physics of the transition is the formation and the rupture of conducting filaments due to the applied bias voltage and thermal effects. This work offers a profound understanding of the mechanism for unipolar switching phenomena.

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