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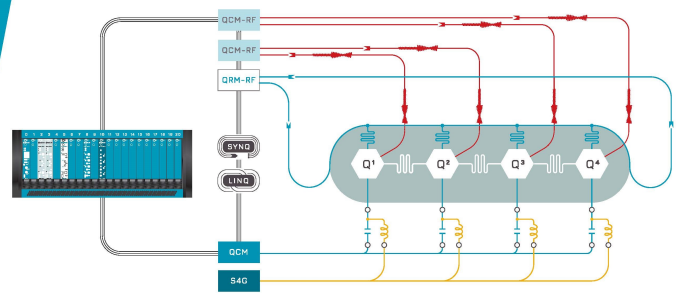
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Predictability of reset switching voltages in unipolar resistance switching

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In unipolar resistance switching of NiO capacitors, Joule heating in the conducting channels should cause a strong nonlinearity in the low resistance state current-voltage (I - V) curves. Due to the percolating nature of the conducting channels, the reset current I_R can be scaled to the nonlinear coefficient B_o of the I - V curves, i.e., $I_R \propto B_o^{-x}$. This scaling relationship can be used to predict reset voltages, independent of NiO capacitor size; it can also be applied to TiO₂ and FeO_y capacitors. Using this relation, we developed an error correction scheme to provide a clear window for separating reset and set voltages in memory operations. © 2009 American Institute of Physics. [DOI: 10.1063/1.3126019]

Unipolar resistance switching (RS) shows reversible bistable resistance states when voltage of the same polarity is applied. It has attracted renewed interest due to its potential application in the nonvolatile memory devices known as resistance change memory (RRAM).^{1,2} However, to apply unipolar RS to a commercial nonvolatile memory device, several reliability-related scientific and technical issues must be resolved. For RRAM, the major current challenge is reducing the error signals due to fluctuations in the switching parameters.² As shown in Fig. 1, the required external voltages for switching between the bistable resistance states fluctuate too much to secure a reliable operational voltage window. Considerable efforts have been expended to solve this fluctuation problem³⁻⁵ but the lack of fundamental understanding regarding the switching mechanism has remained a major obstacle.

Conventional memory devices, such as flash memory and dynamic random access memory, also have error signal problems; the common solution has been to apply error correction techniques with the assistance of advanced circuit designs.⁶ To develop a similar error correction scheme in RRAM, we must find a simple and easily accessible physical phenomenon that can predict the error signals reliably.

Here, we report our attempts at finding a simple physical relationship governing the switch from the low (LRS) to high resistance state (HRS) known as the reset process. Due to Joule heating in the conducting channels, we found that the current-voltage (I - V) curves in the LRS deviated from an Ohmic response and became nonlinear. Although the reset currents I_R fluctuated by about two orders of magnitude, they could be scaled to the nonlinear coefficient of the I - V curves. This simple relationship allows us to predict the reset switching voltages reliably, allowing development of a practical error correction scheme for unipolar RRAM.

The 232 I - V curves of the NiO capacitor represented in Fig. 1(a) show a very wide reset voltage V_R (low-to-high RS) and set voltage V_S (high-to-low RS) distributions. To examine the switching voltage distributions during successive RS operations, we plotted V_R and V_S according to cycle number in Fig. 1(b). V_R and V_S fluctuated widely from 0.3 to 1.4 V and 1.1 to 4.7 V, respectively. The largest value of V_R and the

smallest value of V_S were 1.39 and 1.12 V, respectively. These values indicate the impossibility of making a clear window for the reset and set operation voltages. Overlaps of V_R and V_S will result in irresolvable errors in the RRAM operations.

The inset in Fig. 1(a) shows eight I - V curves in the LRS, chosen from the 232 successive RS operations. Note that the V_R values fluctuated between 0.5 and 0.9 V, and that the I_R value showed even larger fluctuations. Each curve shows a linear Ohmic response at low voltage but a deviation from Ohmic response near V_R . To perform a more quantitative analysis, we evaluated the resistance $R(\equiv V/I)$ of the LRS. As shown in the inset of Fig. 2(a), all eight I - V curves in the LRS can be collapsed into a single line by normalizing with proper values of V_o , where the nonlinearity starts to develop. We assigned the V_o value as the voltage where R became larger by 1% than the resistance R_o value in the limit of $V=0$ V. The collapse in the inset of Fig. 2(a) indicates that there should be a governing mechanism that determines the nonlinear response of the LRS.⁷

Joule heating has been well established to play a very important role in LRS.^{1,8-14} Note that the thermal time constant in most RS devices is known to be less than 10 μ s, much shorter than a typical I - V measurement time.^{8,15} As the percolating conducting filament in LRS is metallic, its local resistance value r should be proportional to its local temperature T : $r(T) = r_o(T_1)[1 + \beta(T - T_1)]$, where β is the temperature coefficient and T_1 is a reference temperature.^{9,10,14} The local current i flowing in part of the filament should provide Joule heating with the power of $i^2 r(T)$, raising T accordingly. Then, $(r - r_o) \propto i^2$. In the percolating network, most of its current will be concentrated in a few singly connected bonds,¹⁶ so $R = R_o + B_o I^2$ (Ref. 17). As shown in Fig. 2(a), all of the curves from the eight LRS fit quite well with $R = R_o + B_o I^2$, indicating the importance of Joule heating in the reset process. Note that B_o , which can be easily measured from a few experimental points on the I - V curve, is a good parameter to represent the Joule heating effects.

Recently, we demonstrated that the connectivity of the conducting filaments in unipolar RS should be similar to those in classical percolation systems.^{5,12,13} In two-dimensional (2D) semicontinuous metal films (i.e., a classical percolating system), studies reported that Joule heating

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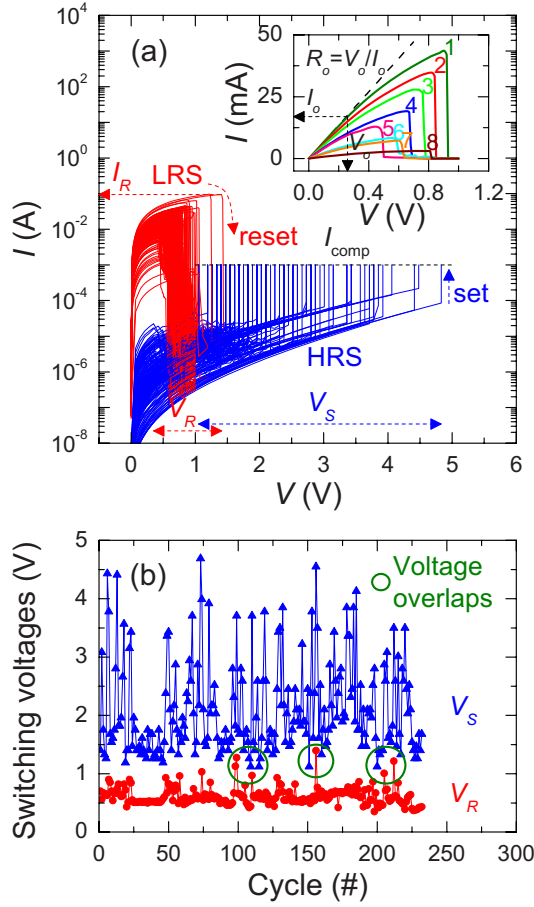


FIG. 1. (Color online) (a) The 322 I - V curves of a NiO capacitor showing unipolar RS. The red and blue lines correspond to the reset and set processes, respectively. To prevent permanent dielectric breakdown during the set processes, we limited the maximum current, called the compliance current I_{comp} , to 1 mA. The inset shows eight LRS-selected I - V curves. Note that each curve shows a nonlinear response when V approaches the reset voltage V_R . I_o and V_o are the current and voltage, respectively, at which nonlinearity begins to develop, and R_o is the resistance in the limit of $V = 0$ V. The current value corresponding to V_R is called the reset current I_R . (b) Wide distributions of V_R and set voltage V_S during 322 successive reset and set processes. Voltage overlaps of V_R and V_S result in irresolvable error signals.

could result in an electric breakdown in the percolating network.^{16,18} The Joule heating could also cause nonlinear responses, including the third harmonic generation.^{16–18} By measuring the third harmonic coefficient B_{3f} (i.e., the ratio between third harmonic voltages and the cube of the applied ac current), Yagil *et al.* showed that the breakdown current should be scaled with B_{3f} in 2D semicontinuous metal films.^{16,18} Note that B_o is the zero-frequency limit of B_{3f} .¹⁷ Therefore, we adopted a simple analogy with our experimental data by replacing B_{3f} with B_o . As shown in Fig. 2(b), where $\log_{10}(I_R)$ versus $\log_{10}(B_o)$ is plotted for our NiO capacitors, we found that $I_R \propto B_o^{-x}$ with $x = 0.3 \pm 0.1$ holds throughout the full range of B_o .

Furthermore, we found that the simple scaling relationship between I_R and B_o holds well, independent of sample size and material system. As indicated by the solid circles in Fig. 2(b), the transport data from the $30 \times 30 \mu\text{m}^2$, $500 \times 500 \text{ nm}^2$, and $100 \times 100 \text{ nm}^2$ Ti-doped NiO capacitors¹⁵ follow the same scaling behavior. Note that the scaling relationship $I_R \propto B_o^{-x}$ is valid over a wide range of B_o (about ten orders of magnitude). Furthermore, as shown in the inset of

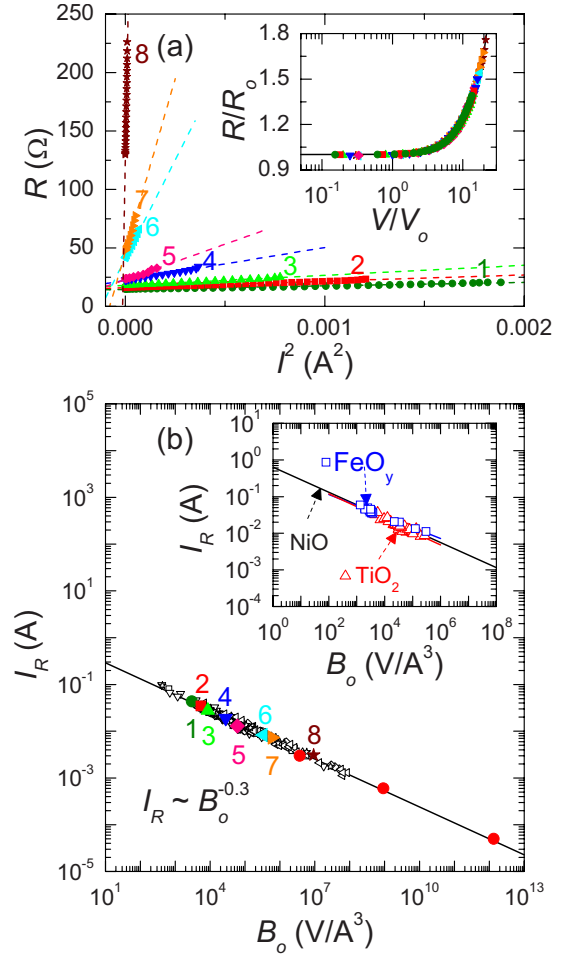


FIG. 2. (Color online) (a) Plots of R vs I^2 . As all the R - I^2 curves are straight lines, fitting by $R = R_o + B_o I^2$ yields B_o and R_o for each LRS from the slope and the y-intercept. The inset shows plots of normalized resistance R/R_o and normalized voltage V/V_o for eight LRS values. Note that all of the R/R_o - V/V_o curves collapse into one line. (b) Plot of $\log_{10}(I_R)$ vs $\log_{10}(B_o)$. Note that a single scaling relationship holds within a full variation in B_o . As denoted by the red solid circles, this scaling relationship persists for Ti-doped NiO capacitors, whose data are from Ref. 15. The inset shows that TiO_2 (triangles) and FeO_y (squares) capacitors have nearly the same x values as the NiO capacitors.

Fig. 2(b), measurements of I_R and B_o data for FeO_y and TiO_2 capacitors⁵ yielded $x = 0.32 \pm 0.05$ and 0.37 ± 0.05 , respectively. Random circuit breaker network model-based simulations^{5,14} also yielded $x = 0.3 \pm 0.1$ (data not shown). These agreements suggest that the scaling relationship of $I_R \propto B_o^{-x}$ could be universal and therefore applicable to other RRAM material systems. Note that the $I_R \propto B_o^{-x}$ scaling relationship suggests that if we enter the LRS via a set process, we can reliably predict the value of I_R for the next reset process by simply measuring B_o .

Based on this predictability, we developed error correction logic for RRAM. Figure 3(a) shows our proposed error correction scheme flowchart. Using the scaling relationship $I_R \propto B_o^{-x}$, the I_R value for the next reset process can be estimated. We can also estimate the resistance value R_R for the next reset process from $R_R = R_o + B_o I_R^2$. Using the relationship $V_R = I_R R_R = I_R (R_o + B_o I_R^2)$, we can predict the V_R value, i.e., $V_R(\text{Pre})$. Then, if $V_R(\text{Pre}) < V_R^{\text{th}}$, the LRS is kept. To change the LRS into HRS, reset switching should occur below V_R^{th} ; however, if $V_R(\text{Pre}) \geq V_R^{\text{th}}$, the LRS is cleared by applying a large enough voltage pulse for the reset and set

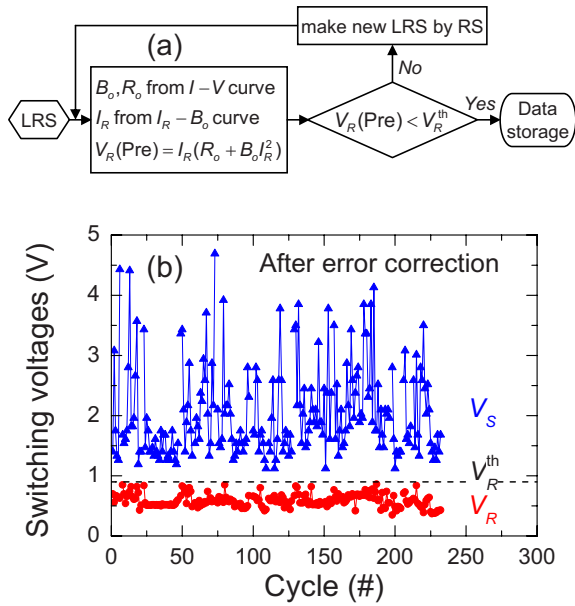


FIG. 3. (Color online) (a) Flowchart to explain the error correction scheme. (b) A clear voltage window opened between V_R and V_S after error correction with a threshold value of $V_R^{\text{th}}=0.9$ V.

operations.^{8,15} The RRAM device then enters the next LRS and the comparison should be redone.

We applied our proposed error correction logic to the data given in Fig. 1. Figure 3(b) shows a clear voltage window between V_R and V_S with $V_R^{\text{th}}=0.9$ V. $V_R(\text{Pre})$ agreed with the experimental V_R values within a relative error of 10%. This removal process guaranteed that all of the LRS values used in the real RRAM operations will be reset with the application of voltages less than 0.9 V.

In summary, we investigated the nonlinear behavior of the current-voltage curves for a Pt/NiO/Pt capacitor, which showed unipolar RS. In the LRS, Joule heating effects cause quite strong deviations from Ohmic behavior. Due to the fractal nature of the conducting filaments in unipolar RS, a scaling relationship $I_R \propto B_o^{-x}$ should exist. Based on this simple physical relationship, we proposed a simple error correction scheme that could provide a clear voltage window for reset and set operations in RRAM.

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