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Set Voltage Statistics in Unipolar HfO_2-Based RRAM

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1. Introduction

Resistive random access memory (RRAM) is considered as one of the most promising candidates for next-generation nonvolatile memory due to its simple structure, excellent scalability and compatibility with standard CMOS process [1]. The control of the statistical variations of resistive switching (RS) parameters is of great importance to successfully push RRAM into application. Researching the statistics of the switching parameters and deepening the understanding of the underlying physical mechanism behind the switching statistics are beneficial to the effective control and trustful forecast of the memory performance [2]. In this work, we show the experimental set statistics of a Pt/HfO_2/Pt RRAM device [3]. Following the analogy with the oxide breakdown (BD) percolation model [4], we propose an analytical model based on the quantum point contact (QPC) conduction model [5], which can fully account for the experimental results.

2. Experiments

The RRAM device with the Pt/HfO_2/Pt structure as shown in the inset of Fig. 1 was fabricated with 10-nm-thick HfO_2 RS layer deposited by atomic layer deposition (ALD) at 350 °C on the Pt bottom electrode (BE), followed by Pt top electrode (TE) deposition and patterning. The *I-V* curves in the 1750 set/reset cycles were tested using DC voltage sweep. During the set transition, a compliance current of 1 mA was applied to avoid the hard breakdown of the HfO_2 layer.

3. Results and discussion

Fig. 1 shows several typical *I-V* curves. The initial R_{off} has strong influence on the current evolution in each set cycle. The competition between set and reset events always exists in each set cycle. Fig. 2 shows the evolution of V_{set} during the 1750 cycles. In Fig. 3, V_{set} shows comparatively wide spread but slightly increases with R_{off}. In order to establish the model describing the correaltion between the statictics of V_{set} and that of R_{off}, those cycles with R_{off} lower than $1/G_0$ and those having well-defined reset event were eliminated from our set statistics. The conductance quantum $G_0 = 2e^2/h$ can be taken as a boundary between HRS and LRS.

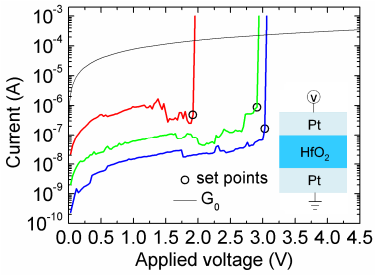

Fig. 1 Typical *I-V* curves in several set cycles. Inset is the schematic structure of the Pt/HfO_2/Pt device.

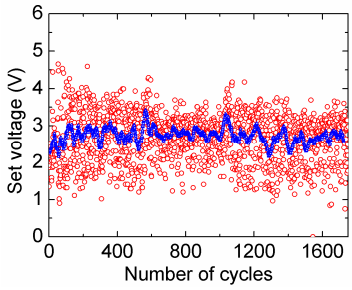

Fig. 2 Evolution of V_{set} during 1750 cycle. Red circles are raw data and blue triangles correspond to a moving average of 25 successive points.

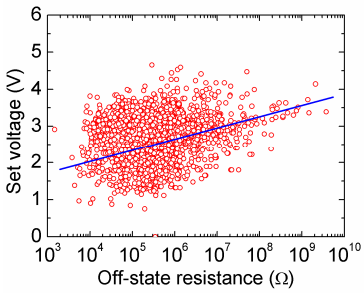

Fig. 3 Scatter plots of V_{set} versus R_{off} in 1750 cycles. The spread of V_{set} is comparatively wide but V_{set} slightly increases with R_{off}.

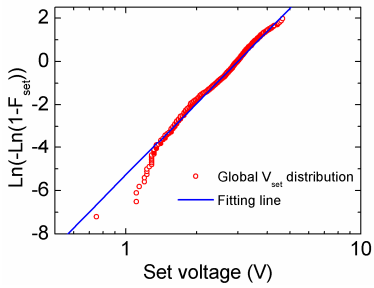

Fig. 4 The experimental global cumulative distribution of V_{set} (points) and the linear fit to a Weibull distribution (straight line).

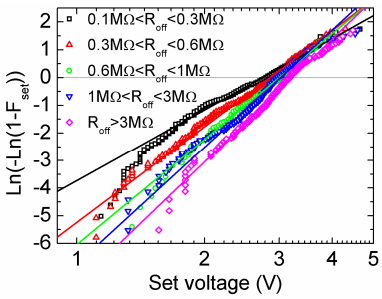

Fig. 5 Decomposition of the experimental V_{set} distribution in 5 different R_{off} ranges (points) and the fitting results (straight lines).

The experimental distribution of V_{set} is close to a Weibull distribution (Fig. 4). Using data screening, we can decompose the global V_{set} distribution and get the statistics of V_{set} as a function of R_{off} (Fig. 5). From Fig. 6, we can find that the

shape factor (i.e. the Weibull slope) and the scale factor of the V_{set} distribution all increase logarithmically with R_{off}.

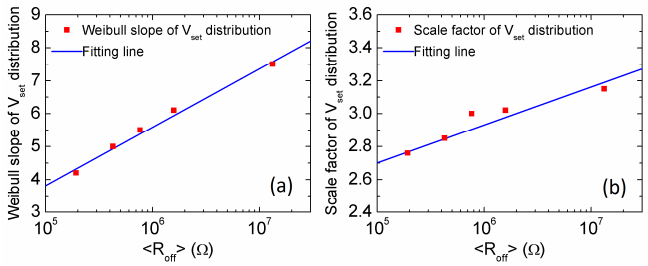

Fig. 6 (a) The relation between the shape factor of the V_{set} distribution versus $<R_{\text{off}}>$. (b) The relation between the scale factor of the V_{set} distribution versus $<R_{\text{off}}>$. $<R_{\text{off}}>$ is the geometric mean of R_{off} in each range.

The cell-based description of the BD percolation path can be useful to model the set statistics of the conductive filament (CF) in RRAM. The shortest gap existing between the remaining CFs after reset and the opposite electrode will determine the set switching. As shown in Fig. 7, this gap can be divided into N columns with each column composed of n cells. If this gap has a length t_{gap} and an area A_{CF}, and each cell has a volume a_0^3, then $N = A_{\text{CF}}/a_0^2$ and $n = t_{\text{gap}}/a_0$. We assume N is constant for all the set cycles and only n changes for the different set events. Defining λ as the probability of a cell being defective (i.e. oxygen vacancies diffuse into the cell region), then the set probability (i.e. the probability of all the $N\times n$ cells in the gap being defective) can be given as $F_{\text{set}} = 1-(1-\lambda^n)^N$. When $\lambda << 1$, the Weibit W_{set} can be approximated as:

$$W_{\text{set}} \cong \text{Ln}(N) + n\,\text{Ln}(\lambda). \quad (1)$$

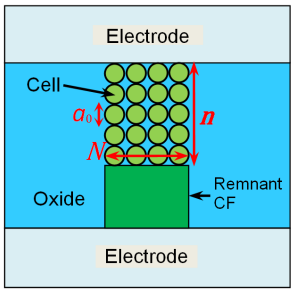

Fig. 7 Schematic representation of the cell-based set model showing the formation of a CF across the shortest gap in the oxide between TE and BE.

When $\lambda \ll 1$, $\lambda \approx n_{\text{DEF}}$, n_{DEF} being the average number of defects per cell which in the case of a voltage ramp stress ($V(t) = Rt$) can be shown to be given by [2]:

$$n_{\text{DEF}}(t_{\text{set}}) = \left(\int_0^{t_{\text{set}}} \frac{1}{\tau_T(t)} dt\right)^{\alpha}. \quad (2)$$

$\tau_T(t)$ is strongly dependent on the oxide field [6]:

$$\tau_T(t) = \gamma_{T0}\left(\frac{V(t)}{t_{\text{gap}}}\right)^{-m}. \quad (3)$$

substituting Eq. (3) and (2) into (1), we get a Weibull model for the distributions of set voltage:

$$W(V_{\text{set}}) = \text{Ln}(N) + (m+1)\alpha n\,\text{Ln}\left\{\frac{V_{\text{SET}}}{[(m+1)R\gamma_{T0}t_{\text{gap}}{}^m]^{\frac{1}{m+1}}}\right\} \quad (4)$$

with the Weibull slope and scale factor:

$$\beta_V = \left(\alpha\frac{m+1}{a_0}\right)t_{\text{gap}} \quad (5)$$

$$V_{63\%} \approx const \cdot R^{\frac{1}{m+1}}(t_{\text{gap}})^{\frac{m}{m+1}} \quad (6)$$

Our model reveals that the Weibull slope β_V is proportional to t_{gap} and the scale factor $V_{63\%}$ slightly depends on the ramp rate R and is also roughly proportional to t_{gap} if m is large.

The QPC model [5] describing the conduction in BD in terms of the change of the barrier of the conductive channel is useful to deal with the conduction in RRAM. The most general equation of the QPC model is:

$$I = \frac{2e}{h}N_{\text{ch}}\left\{eV + \frac{1}{\alpha_{\text{B}}}\text{Ln}\left[\frac{1+exp\{\alpha_{\text{B}}[\Phi_{\text{B}}-\beta eV]\}}{1+exp\{\alpha_{\text{B}}[\Phi_{\text{B}}+(1-\beta)eV]\}}\right]\right\}, \quad (7)$$

where N_{ch} is the number of opened conducting channels, Φ_{B} is the height of the tunneling barrier in the conducting channel, α_{B} is proportional to the thickness of the barrier, β is the fraction of voltage that drops at the cathode interface. For high enough barrier (i.e. deep into the HRS), when $V\to 0$, Eq. (4) can be approximated as $I \cong G_0 N_{\text{ch}}\exp(-\alpha_{\text{B}}\Phi_{\text{B}})V$, so that R_{off} is given by $R_{\text{off}} \cong \exp(\alpha_{\text{B}}\Phi_{\text{B}})/(G_0 N_{\text{ch}})$. In deep HRS, the barrier thickness $t_{\text{B}} = \frac{\hbar\alpha_{\text{B}}}{\pi}\sqrt{\frac{2\Phi_{\text{B}}}{m_0}}$ [5] is equal to t_{gap}. Thus

$$t_{\text{gap}} = \frac{\hbar}{\pi}\sqrt{\frac{2}{m_0\Phi_{\text{B}}}}\text{Ln}(G_0 N_{\text{ch}} R_{\text{off}}). \quad (8)$$

Consequently our model predicts that both β_V and $V_{63\%}$ have a linear relation with $\text{Ln}(R_{\text{off}})$, which is completely in accord with the experimental result as shown in Figs. 6 and 7.

4. Conclusions

The characterization and modeling of the set statistics of the Pt/HfO_2/Pt RRAM device are presented. The electrical measurement shows that both the Weibull slope and the scale factor of the set voltage cumulative distribution increase logarithmically with the off-state resistance. A fully analytical cell-based model on the basis of the quantum point contact model is constructed for the set statistics, whose results are completely in agreement with the experimental results. It is of great importance to control the variations of off- and on-state resistances to achieve the uniform distribution of set and reset parameters.

Acknowledgments

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