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 trustworthy 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 $R_{\text{off}}$ 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 $V_{\text{set}}$ during the 1750 cycles. In Fig. 3, $V_{\text{set}}$ shows comparatively wide spread but slightly increases with $R_{\text{off}}$. In order to establish the model describing the correlation between the statistics of $V_{\text{set}}$ and that of $R_{\text{off}}$, those cycles with $R_{\text{off}}$ 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. 4 The experimental global cumulative distribution of $V_{\text{set}}$ (points) and the linear fit to a Weibull distribution (straight line).

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

The experimental distribution of $V_{\text{set}}$ is close to a Weibull distribution (Fig. 4). Using data screening, we can decompose the global $V_{\text{set}}$ distribution and get the statistics of $V_{\text{set}}$ as a function of $R_{\text{off}}$ (Fig. 5). From Fig. 6, we can find that the
shape factor (i.e. the Weibull slope) and the scale factor of the $V_{\text{set}}$ distribution all increase logarithmically with $R_{\text{off}}$.

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 be divided into $N$ columns with each column composed of $n$ cells. If this gap has a length $t_{\text{gap}}$ and an area $A_{\text{CF}}$, and each cell has a volume $v$, then $N = A_{\text{CF}}/v^2$ and $n = t_{\text{gap}}/v$. We assume $N$ is constant for all the set cycles and only $n$ changes for the different set events. Defining $\lambda$ 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 $\lambda \ll 1$, the Weibull $W_{\text{set}}$ can be approximated as:

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

$$W_{\text{set}} = \ln(N) + (m + 1)\alpha \ln \left(\frac{V_{\text{set}}}{\alpha} - \frac{1}{\alpha} t_{\text{gap}}\right).$$  (4)

with the Weibull slope and scale factor:

$$\beta_{\text{v}} = \left(\frac{m+1}{m}\right) t_{\text{gap}}$$  (5)

$$V_{\text{set}} \approx \text{const} \cdot R_{\text{off}} t_{\text{gap}}^{m+1}$$  (6)

Our model reveals that the Weibull slope $\beta_{\text{v}}$ is proportional to $t_{\text{gap}}$ and the scale factor $V_{\text{set}}$ is slightly depends on the ramp rate $R$ and is also roughly proportional to $t_{\text{gap}}$ 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:

$$I = \text{const} \cdot R_{\text{off}} t_{\text{gap}} \left\{ \exp \left(\frac{1}{\alpha} \ln \left(\frac{V_{\text{set}}}{\alpha} - \frac{1}{\alpha} t_{\text{gap}}\right) \right) \right\},$$  (7)

where $N_{\text{ch}}$ is the number of opened conducting channels, $\Phi_B$ is the height of the tunneling barrier in the conducting channel, $\alpha$ is the fraction of voltage that drops at the cathode interface. For high enough barrier (i.e. deep into the HRS), when $V \rightarrow 0$, Eq. (4) can be approximated as $I \approx \frac{G_{\text{ch}}}{\alpha} \exp(-\alpha \Phi_B V)$, so that $R_{\text{off}}$ is given by $R_{\text{off}} \equiv \exp(\alpha \Phi_B V)/G_{\text{ch}}$. In deep HRS, the barrier thickness $t_B = \frac{h}{\pi} \exp(\frac{2\alpha \Phi_B}{\pi m_0 N_{\text{ch}}})$ [5] is equal to $t_{\text{gap}}$. Thus

$$t_{\text{gap}} = \frac{h}{\pi} \sqrt{\frac{2\Phi_B}{m_0 N_{\text{ch}}}} \ln(G_{\text{ch}} R_{\text{off}})$$  (8)

Consequently our model predicts that both $\beta_{\text{v}}$ and $V_{\text{set}}$ have a linear relation with $\ln(R_{\text{off}})$, 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.

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