Investigation of Thomson Effect in Cu/TaO_x/Pt Resistive Switching Memory

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Resistive memories have attracted considerable attention for overcoming many scaling problems of current nonvolatile memories. The mechanism of resistive switching is attributed to the formation and rupture of conductive nanofilaments (CF). The oxidation reaction and thermally activated dissolution can both induce the rupture of the filament in the RESET process [1] . In this research, we explore the Thomson heating effect induced by the high RESET current of Cu/TaO_x/Pt resistive memory devices.

The heat generated in nanoscale metal filament causes temperature increase when the RESET current is high. This heating effect may dominate the rupture of filament. Thomson effect discovered in 1851 describes the heating or cooling of a current-carrying conductor with a temperature gradient. If a current density J passes through a homogeneous conductor, the heat generation per unit volume q is:

$$q = \rho J^2 - \mu J \frac{dT}{dx} \qquad (1)$$

where ρ is the resistivity of the material, dT/dx is the temperature gradient along the filament, J is the current density, and μ is the Thomson coefficient. The first term is the Joule heating and the second term is the Thomson heating. The Thomson heating depends on the direction of the current flowing through the filament [2] . A significant impact of Thomson effect is reported for PCM cells [3] .

In a cylindrical Cu filament, the two temperature profiles will be mirror symmetric about the center of filament for bipolar and unipolar switching. Therefore there is no difference in the RESET voltages (V_{RESET}). Only asymmetric filament geometry such as cone or truncated cone geometry [4] can generate asymmetric temperature profiles along the filament due to the Joule heating. For a conical nanofilament, the highest temperature is generated at the tip regardless of the current direction. If the Thomson coefficient is large enough, the local heating would be different for RESET operations in unipolar and bipolar switching modes, because the current directions are opposite. In our simulation, the bottom radius of filament is $r_{CF(max)}$ and the top radius is $\alpha \cdot r_{CF(max)}$ ($\alpha < 1$). For any position on the filament, if the distance between the filament tip and this position is x, the radius at this position is

$$r(x) = r_{CF(max)} \left[(1-\alpha)\frac{x}{t_{ox}} + \alpha \right] \qquad (2)$$

The heat diffusion is considered in one dimension along the filament. A heat transfer coefficient h is introduced to model the heat dissipation from the Cu filament to the surrounding oxide [5] . Then Fourier equation is rewritten as

$$\rho_m C_P \frac{\partial T}{\partial t} = k_{th} \frac{\partial^2 T}{\partial x^2} - h \frac{T - T_{ox}}{t_{ox}} + \rho J^2 - \mu J \frac{dT}{dx} \qquad (2)$$

where T is the local temperature along the filament axis, T_{ox} is the oxide temperature, t_{ox} is the oxide thickness, J is the current density, k_{th} is the thermal conductivity, C_P is the specific heat capacity, and ρ_m is the mass density. The Thomson coefficient of bulk Cu is 3 to 6 μV/K between 600 and 1200 K and can be modeled as T/200 (μV/K) where T is the temperature in units of K [6] .

Eqs. (2) and (3) are solved simultaneously. A threshold temperature is defined above which the rupture occurs. V_{RESET} is the voltage at which the peak of temperature profile reaches the threshold. Fig. 1 shows the simulated temperature profiles which indicate a slight increase of V_{RESET} for the unipolar switching assuming the Thomson coefficient to be 200 times that of bulk Cu [6] . Fig. 2 shows the cumulative probability of V_{RESET} measured for the unipolar and bipolar switching of Cu CFs. The difference of V_{RESET} is quite small except for the high voltage range – consistent with the simulation results.

To sum up, the Thomson heating effect is explored with a 1-D heat equation for resistive memory. The simulation of temperature profiles only shows small differences between the bipolar and unipolar switching in high V_{RESET} range of the Cu CFs. This prediction is consistent with experimental data shown in Fig. 2. The statistical V_{RESET} is, however, different for oxygen vacancy (V_O) filaments where a significant shift is seen between the unipolar and bipolar switching. The Thomson coefficient of V_O filament is estimated to fit our experimental observation.

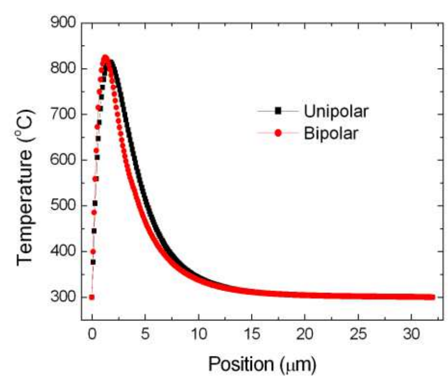

Fig. 1. Simulated temperature profiles of unipolar and bipolar switching in Cu/TaO_x/Pt resistive memory devices.

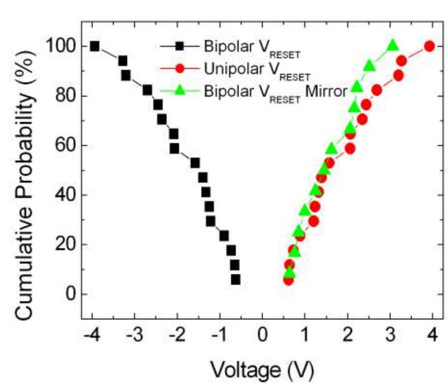

Fig. 2. Cumulative probability of RESET voltages of bipolar and unipolar switching for Cu filament.

References

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