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Reproducing resistive switching effect by Soret and Fick diffusion in resistive random access memory (ReRAM)

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Abstract

It is widely received that resistive switching of resistive random access memory (ReRAM) is caused by formation and rupture of conductive filament consisting of oxygen vacancies, V_O's. However, driving forces that migrate oxygen vacancies are not elucidated yet.

In this paper, reset was attempted by injecting saw-tooth shaped voltage pulses with various rise time, t_{lead}, to a Pt/NiO/Pt cell in a low resistance state. Reset occurred for long t_{lead}, whereas the resistance was rather reduced for short t_{lead}. The latter cannot be explained by generally accepted switching models that assume Fick diffusion and electric field drift. Therefore, we re-examined driving forces and succeeded in reproducing pulse response data for wide t_{lead} range by simulating V_O migration assuming Fick and Soret diffusion. It was suggested that the change of resistance is decided as a result of the competition of Fick and Soret diffusion.

1. Introduction

A filament model, in which a conductive filament (CF) consisting of oxygen vacancies (V_O's) is formed in the metal oxide (MO) film of an EL/MO/EL structure by a forming process and the resistive switching effect is caused by generation and repair of oxygen vacancies, is widely accepted, where EL and MO represent electrode and metal oxide, respectively.[1)] However, driving forces of V_O migration that cause reset and set switching are still unclear. Koh *et al*. reported that the oxygen reservoir of a Pt/NiO/Pt structure is the NiO film itself surrounding the CF.[2)] Therefore, a driving force that is different from an electric field drift that is perpendicular to the EL interface is required to cause set switching. One of the candidates for this driving force is the Soret force, which works in the direction of the temperature, T, gradient.[3)]

In this paper, we examined Soret diffusion as a driving force instead of electric field drift of V_O's. We succeeded in reproducing pulse response data for wide rise time, t_{lead}, range by simulating V_O migration assuming Fick and Soret diffusion as driving forces. The change of resistance is suggested to be decided by the relative magnitude of Fick and Soret diffusion.

2. Experiment

Reset was attempted for Pt(100nm)/NiO(60nm)/Pt (100nm) cells in a low resistance state (LRS) that have resistance, R_{LRS}, of 70-120 Ω by injecting a saw-tooth shaped voltage pulse with the rise time of t_{lead} as shown in the inset of Fig. 1(a). The pulse height, V_p, was increased from 0.3 to the V_p at which reset switching or reduction of R_{LRS} was confirmed in steps of 0.1 V.

Reset was attempted by simulating V_O migration using commercial software (COMSOL Multiphysics). We assumed Soret and Fick diffusion, whereas electric field drift and Fick diffusion are generally adopted as driving forces of V_O migration.

3. Results and Discussion

Figs. 1(a) and (b) show typical current responses to injected saw-tooth shaped voltage waves with t_{lead} of 3 ms and 30 μs, respectively. Reset did not occur for t_{lead} = 30 μs and the R_{LRS} was reduced to the value smaller than 0.9 times the initial R_{LRS} value at V_p = 0.9 V, whereas reset occurred at V_p = 0.8 V for t_{lead} = 3 ms. Fig. 2 shows V_p dependences of resistances for t_{lead} = 300 ms, 3 ms, and 30 μs. The occurrence of reset was confirmed for t_{lead} = 300 ms and 3 ms, whereas R_{LRS} was reduced for t_{lead} = 30 μs.

Reset switching was attempted by the simulation in which Fick ($\propto dn_{Vo}/dr$) and Soret ($\propto dT/dr$) diffusion are assumed to be driving forces for V_O migration. Fluxes of V_O's for Fick and Soret diffusion, J_{Fick} and J_{Soret}, are as follows:

$$J_{Fick} = D_{Vo}\, dn_{Vo}/dr, \quad (1)$$

$$J_{Soret} = -D_{Vo} S_{Vo} n_{Vo}\, dT/dr, \quad (2)$$

where D_{Vo}, n_{Vo}, and S_{Vo} are the diffusion constant, the density, and the Soret coefficient of V_O's as a function of the radial coordinate, r, respectively, assuming a cylindrical cell structure (Fig. 3(a)). The electric conductivity of CF and the NiO film is assumed to be $\sigma = \sigma_0 \exp(-E_a/k_BT)$, where σ_0 and E_a as a function of n_{Vo} were given by Figs. 3(b) and (c), respectively, and k_B is Boltzmann constant.

The resistance increased with increasing the voltage when saw-tooth wave with t_{lead} andV_p of 1.80 ms and 0.72 V, respectively, was injected (Fig. 4(a)). On the other hand, the resistance decreased by 7% after the application of saw-tooth wave with t_{lead} andV_p of 1.80 μs and 1.02 V, respectively (Fig. 5(a)). V_O's consisting of the CF receive the force by Eq. 1 toward the outside of the CF because n_{Vo} in the CF is higher than that of the outside of CF. On the other hand, V_O's receive the force toward a current path that is a heating center owing to

Joule heating from the surrounding area because T in the CF is higher than that of the outside of CF (Fig. 6(a)). Therefore, when t_{lead} is long enough to maintain thermal equilibrium continuously, J_{Soret} is small because dT/dr in Eq. 2 becomes small (black line in Fig. 6(b)) and the occurrence of reset is confirmed (A ⇒ C in Fig. 4(b)). However, when t_{lead} is short so that thermal equilibrium cannot be maintained, the shorter the t_{lead} becomes, the larger dT/dr becomes (red line in Fig. 6(b)), making J_{Soret} dominant and reset switching is prevented (D ⇒ F in Fig. 5(b)).

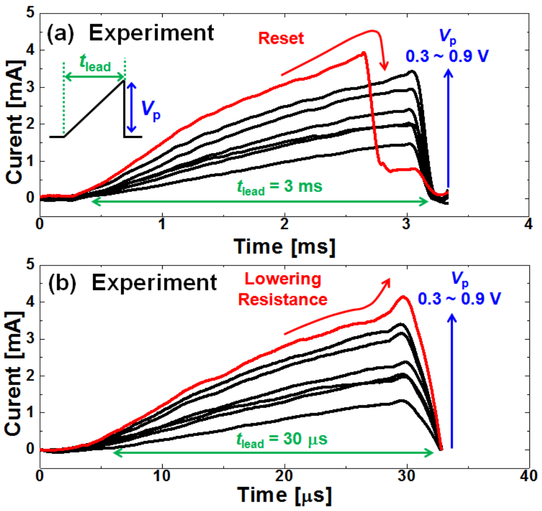

Fig. 1 Typical current responses to injected saw-tooth shaped voltage waves with the rise time, t_{lead}, of (a) 3 ms and (b) 30 μs. Inset: Saw-tooth shaped voltage wave used in this study.

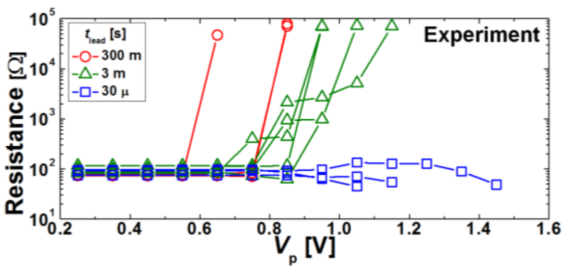

Fig. 2 Vp dependences of resistances for tlead of 300 ms (circles), 3 ms (triangles), and 30 μs (squares).

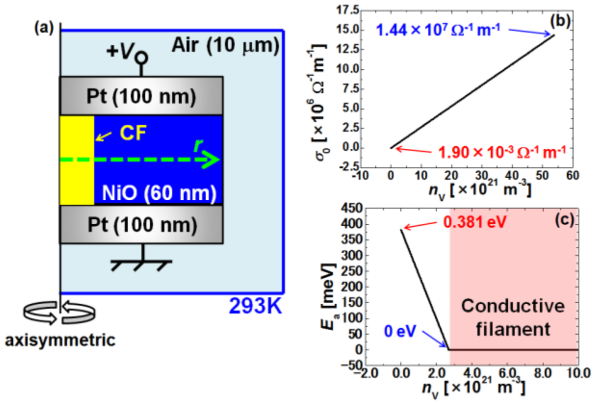

Fig. 3 (a) Cylindrical cell used for the simulation of V_O migration. (b) σ_0 and (b) E_a as a function of n_{V_O}.

4. Conclusions

Experimentally obtained pulse response property can be reproduced successfully by the simulation that involves Soret and Fick diffusion without assuming electric field drift.

References

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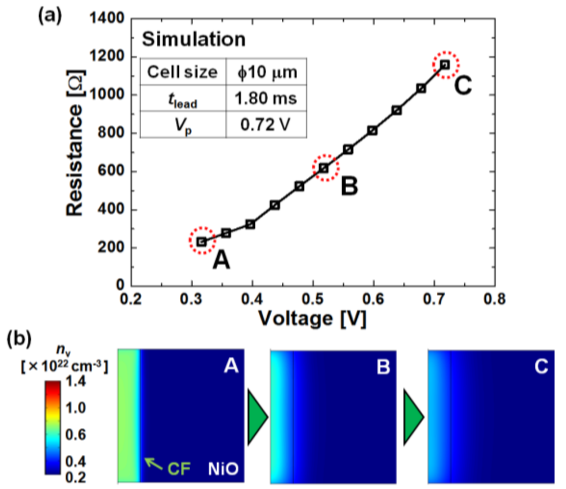

Fig. 4 (a) Voltage dependence of resistance during the application of saw-tooth shaped voltage with t_{lead} and V_p of 1.80 ms and 0.72 V. (b) n_{V_O} distribution at A, B and C in (a).

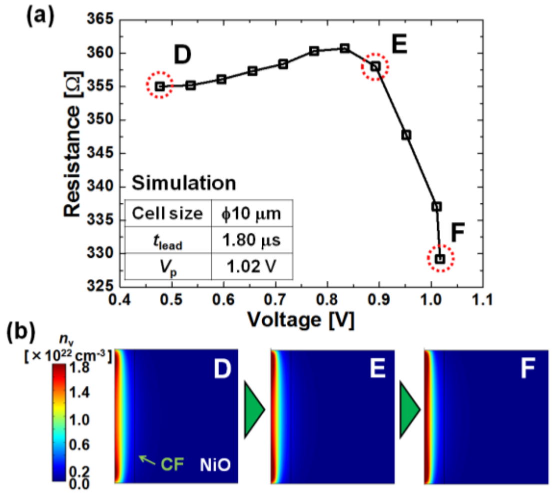

Fig. 5 (a) Voltage dependence of resistance during the application of saw-tooth shaped voltage with t_{lead} and V_p of 1.80 μs and 1.02 V. (b) n_{V_O} distribution at D, E and F in (a).

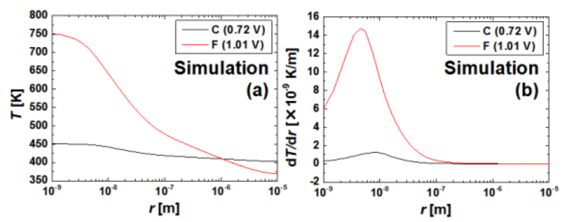

Fig. 6 r dependences of (a) T and (b) dT/dr distribution along the radial coordinate, r, at C in Fig. 4 (black line) and F in Fig. 5 (red line).