Accelerated Retention Test Method by Controlling Ion Migration Barrier of ReRAM

YunMo Koo, Stefano Ambrogio, Jiyong Woo, Jeonghwan Song, Daniele Ielmini, and Hyunsang Hwang

Abstract— **Retention of the low resistance state (LRS) in resistive random access memory (ReRAM) significantly decreases at increasing electrical stress due to barrier lowering of ion migration and Joule-heating. LRS failure rate under externally applied bias could be modeled by adopting an Arrhenius equation for ion migration. Accelerated retention failure under voltage stress is explained by the combination of two effects: a) lowering of the ion migration barrier by external electric field and b) thermal energy enhancement through local Joule-heating. Based on this model, an improved methodology for ReRAM data retention test is proposed, allowing to reduce the testing temperature and the experimental time by several orders of magnitude by applying a relatively-low voltage.**

Index Terms- **ReRAM, retention, accelerated test.**

I. INTRODUCTION

Recently, the reliability study of resistive random access memory (ReRAM) has been the subject of intense research, to fully assess the capability of ReRAM to replace Flash NAND memory technology [1-5]. Among the various reliability aspects, data retention is a key issue of ReRAM as a non-volatile memory technology. Since filamentary ReRAM relies on defect drift/diffusion at the atomic scale, the ion migration barrier (or activation energy, E_A) plays a key role in data retention. Consequently, several reports have attempted to estimate E_A for fast prediction of data retention in the low resistance state (LRS), assuming a constant value of the migration barrier for a specific state of ReRAM device [1-5]. Previous works, however, have indicated that the energy barrier is affected by the externally applied bias through Joule heating and barrier lowering effects [9, 11].

This study demonstrates that E_A of LRS retention can be lowered by applying an electric field. We show that even a small external bias in the retention test induces an increase of the LRS failure rate by orders of magnitude. Neglecting the field effect can thus lead to a significant inaccuracy in estimating the data retention time. On the other hand, the external field is beneficial in improving the methodology of data retention evaluation at lower temperature by reducing
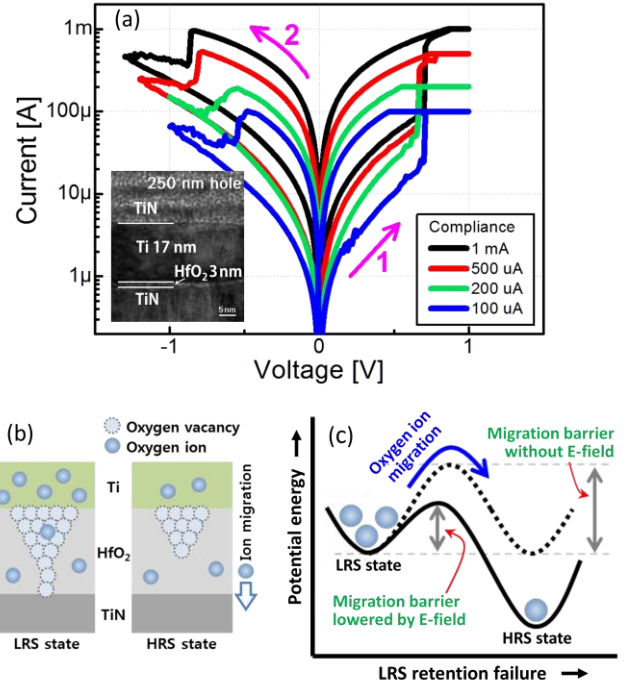
Fig. 1. (a) Typical switching characteristics of the HfO$_2$ based ReRAM. TEM cross section image is shown in the inset. (b) Switching mechanism of the HfO$_2$ based ReRAM: the formation / rupture of oxygen vacancy CF by oxygen ion migration. (c) Schematic diagram of ion migration barrier lowering by external electric field. [8]

measurement time and reducing experimental temperature to minimize device damage.

II. EXPERIMENTS

We fabricated filamentary ReRAM devices with a TiN / Ti / HfO$_2$ / TiN structure deposited within a 250 nm diameter hole (see inset of Fig. 1a). The hole was obtained on TiN / SiO$_2$ / Si wafer by growing 1000 Å of SiO$_2$ insulation layer, patterning, and etching. The switching layer of 3 nm HfO$_2$ layer was deposited by Atomic Layer Deposition (ALD), while other layers were deposited by RF reactive sputtering.

III. RESULTS AND DISCUSSION

Fig. 1a shows typical I-V curves of our ReRAM devices at increasing compliance current I_C. The bipolar switching curves show set at positive and reset at negative voltage, with the LRS resistance and reset state being controlled by I_C. Set/reset processes in HfO$_2$-based ReRAM are due to the formation/
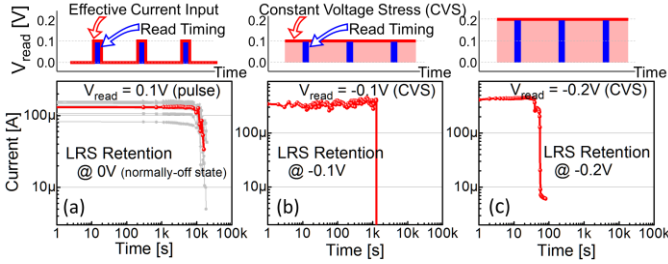
Fig. 2. Results of LRS retention test at 200 ℃ with different read signal conditions. (a) By pulse read signal (for normally-off state, electrical input is minimized). Mean time for LRS failure was 13ks. (b), (c) By CVS read signal with amplitude of -0.1V and -0.2V respectively. The external bias accelerated LRS failure, faster failure rates at higher bias.
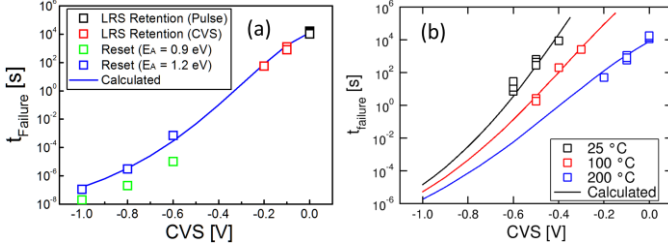

Fig. 3. (a) LRS retention failure time at 200 ℃ under external CVS: both thermal energy and external electric field can accelerate LRS failure. (b) LRS failure time under several CVS and temperature condition. LRS failure accelerated by two influences: 1) The migration barrier lowering by external electric field, and 2) thermal energy from local Joule-heating of CF.

rupture of a conductive filament (CF) consisting of oxygen vacancies in response to the external electric field and consequent local Joule-heating (Fig. 1b) [5-10]. Models of set/reset processes have been developed by describing ion migration through drift/diffusion equations of ion transport [8-9]. According to an analytical model, set operation can be described by an Arrhenius rate equation for the growth of the CF according to [11]:

$$Rate = Ae^{-\frac{E_{A0}-\alpha qV}{kT}} \tag{1}$$

where E_{A0} is the migration barrier at zero externally applied bias, α is the barrier lowering factor, and V is the externally applied bias. According to this model, the ion migration barrier is lowered by the external electric field, while the ionic hopping rate is accelerated by the local temperature increase, which can be estimated by the analytical Joule heating formula (Fig. 1c):

$$T = T_0 + V^2\frac{R_{th}}{R} \tag{2}$$

where T_0 is the ambient temperature and R_{th} is the effective thermal resistance describing the ratio between dissipated electric power $P = V^2/R$ and the local temperature increase [9]. Thermal energy for ion migration is supplied from the ambient and the joule-heating. According to Eqs. (1) and (2), resistance switching occurs at a critical electric field, when the oxygen ions have enough thermal energy to jump over the lowered barrier [7-9].

The same analytical model can be used to describe LRS retention failure. Similar to reset switching, LRS retention failure mechanism is caused by the rupture of the CF due to
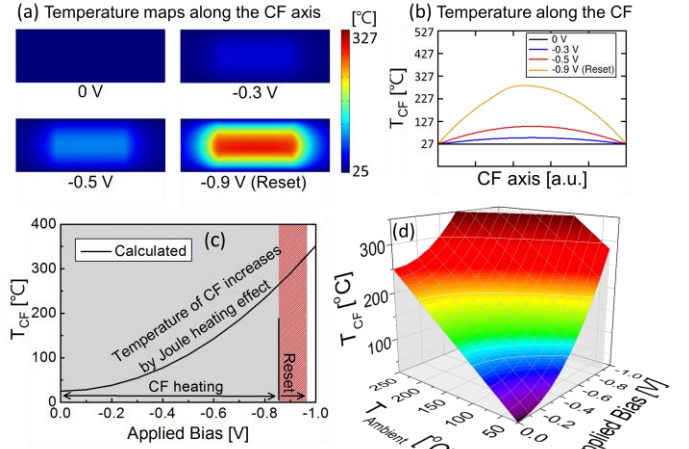

Fig. 4. (a) Temperature map along the CF axis at ambient temperature of RT (25 ℃) with bias of 0V, -0.3V, -0.5V, and -0.9V respectively. Temperature of CF increases by Joule-heating, reaching up to 300℃ at the moment of reset. (b) Temperature profile along the CF axis at each bias. (c) Temperature of CF increases steeply with increasing bias. (d) Both ambient temperature and external bias can supply thermal energy to CF, increasing the temperature of CF.

oxygen ion migration and recombination with an oxygen vacancy of the CF [12]. Eq. (1) also includes influences to the stability of CF from intrinsic reasons such as the built-in potential corresponding to the work function difference. In a usual retention test, the ambient temperature is raised to accelerate the spontaneous CF dissolution. Based on Eqs. (1) and (2), however, CF dissolution might also be accelerated by externally applied voltage.

To test the impact of the external bias on retention, Fig. 2 compares retention tests at 200°C for increasing external bias of 0 V (a), -0.1 V (b) and -0.2 V (c). The read signal was applied once every 5 minutes to minimize disturb in Fig. 2a (0 V stress), while a constant voltage stress (CVS) was applied both to accelerate the test and to read the device in Fig. 2b and c. The results show faster dissolution at increasing bias, meaning that the CVS accelerated LRS failure in Fig. 2b and c.

Fig. 3a shows the retention time t_{fail} as a function of the accelerating bias, indicating that CVS can enhance failure rate by decades. The figure also shows reset switching data with a voltage larger than 0.5 V (absolute value) for comparison. Interestingly, both retention and reset data can be well predicted by calculations using an analytical model for voltage-driven filament dissolution [9], which further supports the common nature of retention and reset switching in LRS. CVS data at increasing ambient temperature in Fig. 3b are also accounted for by the analytical model. A migration barrier E_{A0} = 1.14 eV was used in the calculations, which is in good agreement with previous studies [8-10]. Calculations in Fig. 3 also include local Joule heating in the CF: According to our calculations, the CF temperature of the device increased from an ambient temperature of 25°C to about 300℃ at -0.9 V (Fig. 4). The local CF temperature increases with the ambient temperature and the external bias according to Eq. (2).

In addition to Joule heating, CF dissolution is also accelerated by the barrier lowering under bias. To test this
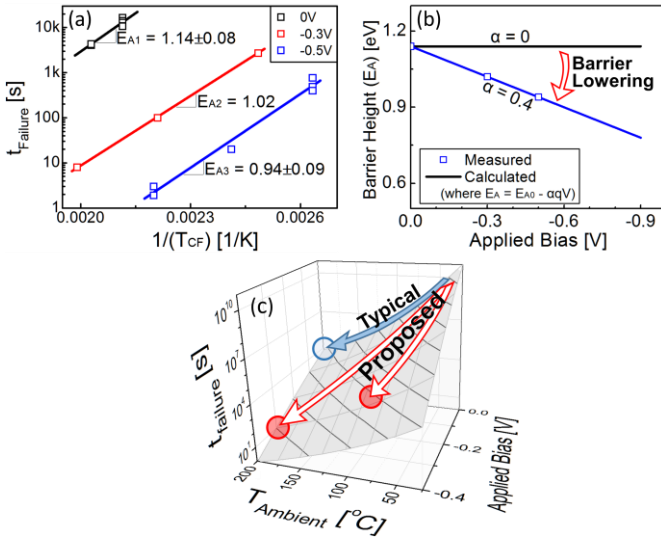
Fig. 5. (a) The effective migration barrier calculated by local temperature of CF. Under external bias, the barrier height lowers. (b) The barrier for the LRS retention of the HfO$_2$ based ReRAM is lowered under bias by lowering factor of 0.4. (c) Proposed LRS retention test method: Retention test can be done at lower temperature, and in several orders-shorter time scale.

concept, Fig. 5a shows the Arrhenius plot of $t_{failure}$, where the observed slope decreases with the external voltage during CVS. From these results, we evaluated a barrier lowering factor α = 0.40 (Fig. 5b) in close agreement with previous results [8, 9]. These results imply that the LRS failure mechanism is universal: thermal energy drives oxygen ion migration by jumping over the barrier, while the external electric field lowers the barrier, accelerating the migration. If the barrier lowering is ignored in estimating the failure time, the LRS failure rate can be inaccurately predicted by several orders. According to the results above, CVS can provide an improved LRS retention test methodology, as discussed in Fig. 5c. The application of a relatively small voltage allows to accelerate retention failure by several orders of magnitudes, thanks to Joule heating and barrier-lowering. In turn, retention test can be performed at a lower temperature, since the external bias can supply thermal energy by Joule-heating. The CVS technique can thus allow for a useful accelerated retention test approach for fast prototyping and testing ReRAM at both single cell and array levels.

IV. CONCLUSION

Our study of retention in HfO$_2$ ReRAM shows that an external CVS accelerates LRS retention failure thanks to Joule heating and migration barrier lowering. LRS failure was modeled by adopting an Arrhenius equation for ion migration. Based on these results, we propose CVS as a fast device test method at lower ambient temperature to accelerate the LRS retention test and maintain relatively low ambient temperature during the retention test.

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