Random Telegraph Noise analysis in Redox-based Resistive Switching Devices Using KMC Simulations

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***Abstract*—This paper presents a physical model to investigate the random telegraph noise (RTN) as an important source of the stochastic variability in redox-based resistive switching RAMs. Our noise analysis showed a higher level of instability during the high resistance state, where the oxygen vacancies, as the dominant traps inside the oxide, assist the current flow. The role of some important factors like read and reset voltages on the fluctuations of the reading process was studied.**

I. Introduction

Redox-based resistive switching RAMs (ReRAMs) are currently under massive studies as one of the most appealing candidates for the next generation of nonvolatile memories (NVM), due to their high density, fast switching speed and low power consumption [1]. The resistance change process in ReRAMs seems to be due to generation and annihilation of conductive filaments (CFs), which may consist of oxygen vacancies, corresponding to low and high resistance states (LRS), (HRS), respectively [2], [3]. Variability of the switching parameters due to the stochastic nature of the switching process is one of the major problems limiting ReRAM technology. Continuing our previous works about studying the cycling variability during the electroforming [4] and the set and the reset processes [5], RTN as one of the intrinsic variability sources in memory devices ([6], [7]) has been studied in this work. The physical mechanisms governing the RTN current fluctuations in ReRAM are not fully understood yet. The RTN, which is generally related to the capture and emission of electrons by vacancies, is mostly observed in the HRS [8]. This is consistent with reports that introduce the trap assisted tunneling (TAT) process as the main conduction mechanism in the HRS [9], [10].

In this paper the RTN-related current fluctuations and their properties in a ReRAM are investigated by the kinetic Monte Carlo (kMC) method. An analysis of the RTN fluctuations in terms of the influence of the resistance state (high or low resistance state), read voltage, read time and reset stop voltage on the instability of the read process is presented.

II. Model Description

In order to model the forming and the set and reset processes a kMC approach has been developed to describe the generation, recombination and diffusion of the oxygen vacancies inside the oxide. The main driving forces running these processes are the electric field, temperature and temperature gradient. The charge transport mechanism in this model is determined by the vacancy distribution at each time. At low vacancy concentration referring to the HRS a combination of direct tunneling and defect-defect tunneling conduction mechanisms is considered. A trap assisted tunneling (TAT) current solver including these conduction mechanisms has been developed to calculate the electron flux through the oxide in the HRS. At high vacancy concentration referring to the LRS the conduction mechanism is switched to an electron drift mechanism. In order to calculate the leakage current through the oxide in this case the drift-diffusion equations are solved self-consistently with the Poisson equation.

III. Simulation Results and Discussion

The kMC simulation result of the current-voltage characteristics is shown in figure 1 including the initial forming process followed by a couple of consecutive switching loops with a current compliance, $I_C = 100\mu A$. Figure 2 shows the current fluctuation during HRS under an applied very slowly ramped voltage (-6 mV/sec), where the larger and smaller jumps are due to vacancy fluctuations and electron trapping/de-trapping processes, respectively. The latter is responsible for the oxygen vacancy induced RTN variability. A vacancy fluctuation here means the addition of a new vacancy into the conductive filament or the removal of a vacancy from the filament. This leads to a structural change of the filament, which should be excluded from the current fluctuations to study the RTN effect specifically [6].

The random change of the read current in the LRS and the HRS under a constant applied voltage is demonstrated in figure 3(a). The RTN pattern, known as the current fluctuation between discrete levels, is obviously only observed in the HRS. In this plot $\Delta I/I$ is defined as $(I_{max} - I_{min})/I_{min}$. As shown in this figure the $\Delta I/I$

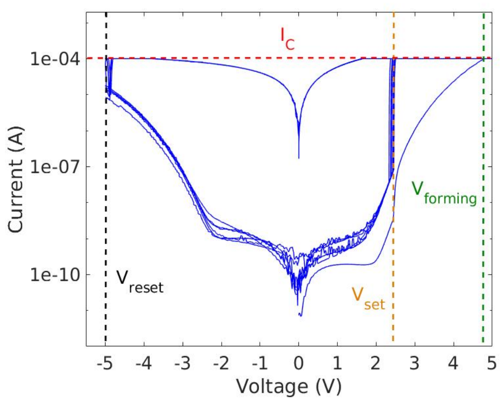


Fig. 1. Current-voltage plot with initial forming and following switching processes in a RERAM at $I_C = 100\mu$A.

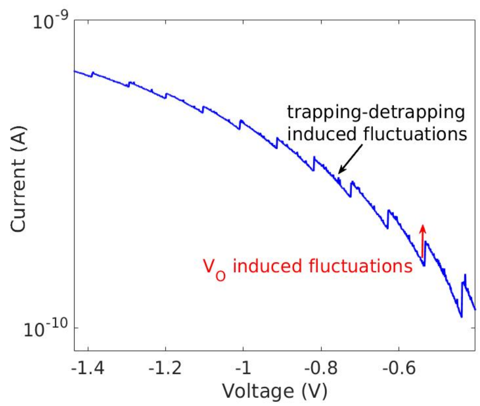
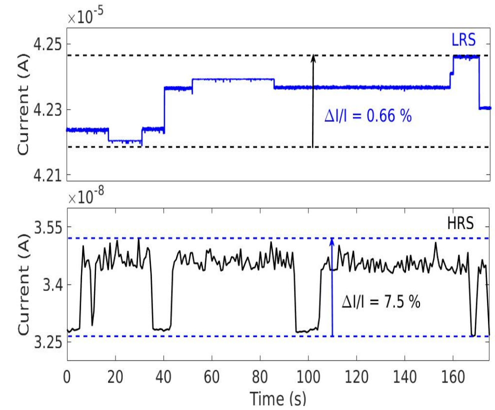
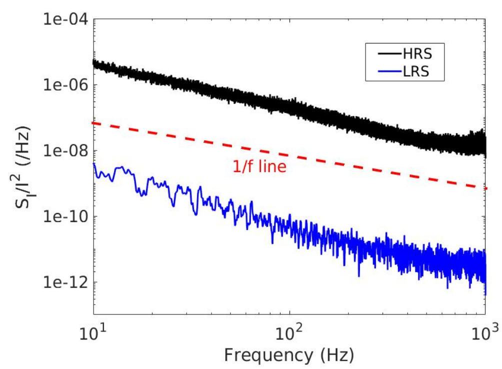


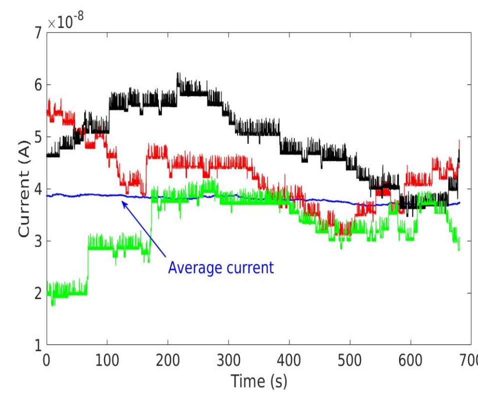
Fig. 2. Current fluctuation under an applied negative very slowly ramped voltage during the HRS. The smaller jumps correspond to the repeatable trapping/de-trapping of an electron at a vacancy site causing the RTN. The larger jumps correspond to the vacancy diffusion in and out of the conductive filament leading to the structural changes.



(a)



(b)



(c)

Fig. 3. (a) ΔI versus time under a constant applied voltage in the HRS (b) Average PSD profile of RTN versus frequency in the HRS and LRS (average of 100 simulations) (c) couple of the current fluctuation signals during read time in the HRS and the average of 100 processes.

value for the HRS is 7.5%, while this value is only 0.66% for the LRS. This higher RTN-related instability in the HRS comes from the activation and de-activation of the vacancies assisting the TAT process. The power spectral density (PSD) profile in the HRS and LRS, plotted versus frequency in figure 3(b), was calculated by averaging over 100 simulations. It shows that in both resistance cases we have a behavior close to $1/f$ noise and the PSD value of the HRS is more than 2 orders of magnitude greater than the LRS. Figure 3(c) shows a couple of the realizations of the RTN process during the read time in the HRS and the average signal. It shows that the average value of the current does not change with time, ensuring that there is no violation of stationarity.

The read voltage, V_{read}, has an important influence on the RTN characteristics. Figure 4(a) shows the RTN current fluctuation, ΔI, versus read current, I_{read}, for an increasing V_{read} in the same HRS and the average over 100 cycles. Here we consider I_{read} as the average value of the signal. ΔI, in this work is defined as the difference between maximum and minimum value of the current. The read time for each process is 60 s. It is expected that ΔI increases with higher I_{read} and accordingly higher V_{read}. This is due the fact that the probability of structural change of the filament increases for higher

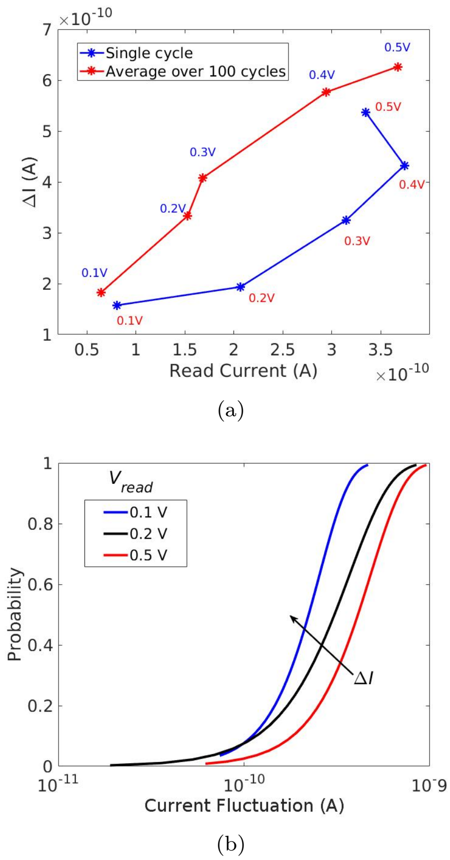


Fig. 4. (a) The relation between RTN-related ΔI and I_{read} in the HRS for a single switching cycle and the average over 100 cycles (b) ΔI probability distribution for for different V_{read}.

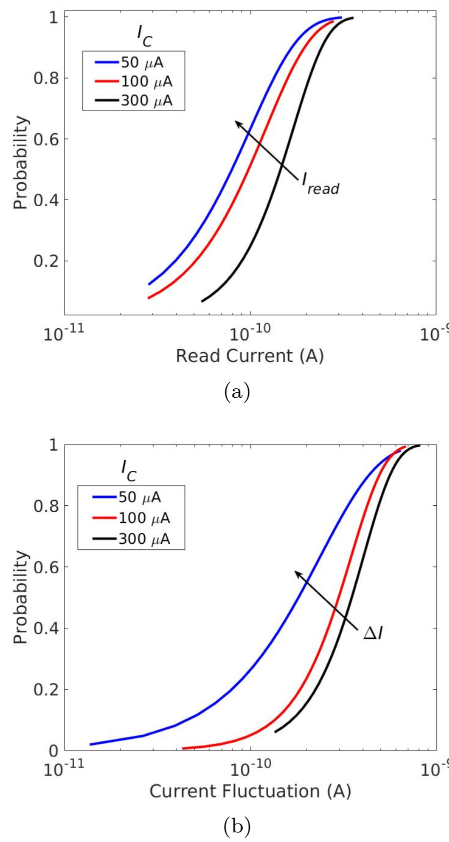


Fig. 5. The probability distribution of (a) I_{read} and (b) RTN-related ΔI for different I_C.

voltages. This results from the barrier lowering of the vacancy diffusion inside the oxide, which is proportional to the applied voltage. But as it can be seen (figure 4(a)) in the case of a single cycle for higher V_{read} this trend is not followed. This is due to the physical change of the filament structure, that is more probable for higher V_{read}. The same figure shows that if we take an average over 100 switching cycles the effect of the structural changes is no longer observed, which indicates that it happens only in a few cycles. The statistical distribution of the RTN-related read current fluctuations, ΔI, in figure 4(b) for different V_{read} also confirms the increase of the RTN-related current instability for higher V_{read}. As it was shown the current fluctuation is proportional to I_{read} and if we manage to decrease I_{read}, we could lower the RTN noise level. One of the ways to reduce the current level is manipulating the forming conditions by decreasing I_C. A smaller I_C results in a thinner conductive filament, which has a smaller density of oxygen vacancies and consequently lower I_{read}. The statistical distribution of I_{read} during 100 switching cycles for three different $I_c = 50\ \mu$A, $I_c = 100\ \mu$A and $I_c = 300\ \mu$A is demonstrated in figure 5(a). The lowest I_{read} belongs to the smallest $I_C = 50\mu$A. Figure 5(b) shows the corresponding probability distribution of ΔI. As expected the value of the current instability decreases for the smaller I_C.

Another important factor to influence the fluctuation of the read signal is the read time. If it is assumed that the PSD is proportional to $1/f^{(1+\alpha)}$, where α is the factor showing the deviation from $1/f$ noise, then the variance of the read current, $\sigma^2_{I_{read}}$, can be calculated as follow

$$\sigma^2_{I_{read}} = \frac{1}{\pi t_{read}} \int_{f_{min} t_{read}}^{\infty} \frac{k}{(\frac{\nu}{t_{read}})^{1+\alpha}} \frac{1-\cos(\nu)}{\nu^2} d\nu \qquad (1)$$

where k is a proportionality constant, $\nu = f t_{read}$ is the normalized frequency and the lower cut-off frequency $f_{min} = t^{-1}_{read}$. Using the above formula, one can conclude that $\sigma_{I_{read}} \propto t^{\alpha/2}_{read}$. This shows that the mean square of the fluctuations increases with the duration of each realization of the reading process [11]. This effect is plotted in figure 6. It shows the distribution of the read current fluctuations for different read times in the HRS, where the ΔI increases with the read time.

The PSD profile and the normalized read current fluctuation under different applied reset voltages in figure 7(a) and 7(b) show that the bias condition has almost no effect on $\Delta I/I$ distribution and the noise PSD, which means it is an intrinsic property of current conduction.

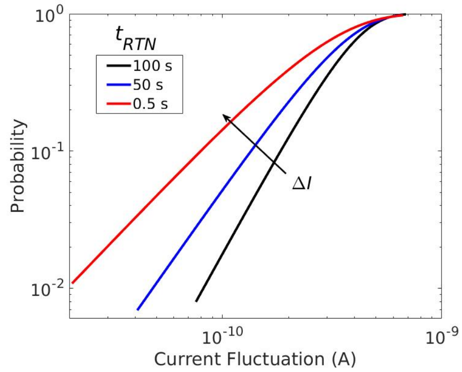
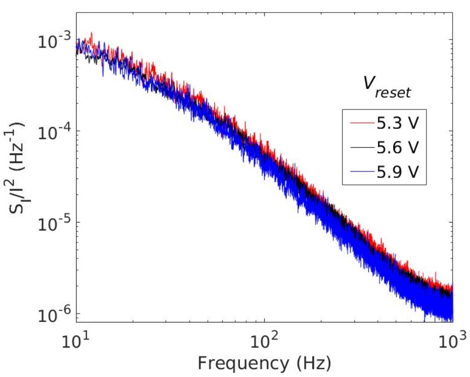
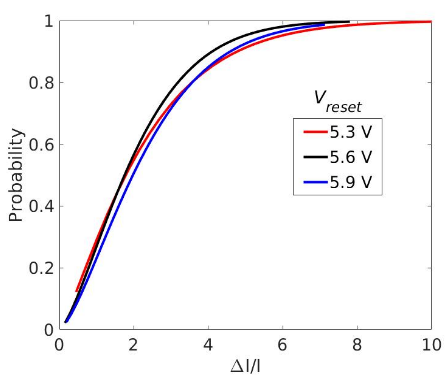


Fig. 6. RTN-related current fluctuations, ΔI, increase with read time growth



(a)



(b)

Fig. 7. (a) PSD profile and (b) $\Delta I/I$ probability distribution in the HRS for different bias conditions.

IV. Conclusion

In this paper the RTN-based variability in ReRAM devices was statistically investigated using a developed kMC model to gain a better understanding of the device behavior. The results showed that the RTN embedded fluctuations, which can be explained as electron trapping and de-trapping by oxygen vacancies inside the oxide, mainly exist in the HRS. This is related to the TAT conduction mechanism in this state. The dependency of RTN-related perturbations during the read process on different factors like resistance state, read conditions and reset voltage was studied.

Acknowledgment

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