Modeling of electron conduction in contact resistive random access memory devices as random telegraph noise

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(Received 27 October 2011; accepted 1 February 2012; published online 2 April 2012)

The intense development and study of resistive random access memory (RRAM) devices has opened a new era in semiconductor memory manufacturing. Resistive switching and carrier conduction inside RRAM films have become critical issues in recent years. Electron trapping/detrapping behavior is observed and investigated in the proposed contact resistive random access memory (CR-RAM) cell. Through the fitting of the space charge limiting current (SCLC) model, and analysis in terms of the random telegraph noise (RTN) model, the temperature-dependence of resistance levels and the high-temperature data retention behavior of the contact RRAM film are successfully and completely explained. Detail analyses of the electron capture and emission from the traps by forward and reverse read measurements provide further verifications for hopping conduction mechanism and current fluctuation discrepancies. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3691224>]

I. INTRODUCTION

During the last decades, semiconductor manufacturing technology has persistently sought to increase data throughput and device density in integrated circuits by device miniaturization. In the context of nanoscale semiconductor memory applications, novel structures and materials have addressed fundamental issues regarding conventional charge-storage memory. Recently, resistive random access memory (RRAM) has emerged as a promising candidate for next-generation nonvolatile memory (NVM) applications. However, our limited understanding of the resistive switching mechanism is a challenge for future device design and development.

Many studies have focused on the origin of the resistive switching characteristics of RRAM devices. The hysteretic resistance switching of Schottky junctions can be explained by the charging and discharging of electrons in oxygen vacancies, resulting in the modulation of the Schottky tunnel barrier width.^{1,2} In addition, two models were proposed to clarify the switching mechanism of metal-oxide-based RRAMs: one involving the self-accelerated thermal dissolution of the conductive filament,³ and the other involving ion transport recombination induced by electron hopping between oxygen vacancies.^{4,5} These hypotheses yielded partially similar results, depending on the material nature of the RRAM dielectric films, leading to dissimilar resistive switching conjectures.

Random telegraph noise (RTN) signals, which are extensively used to study electron transport in high-*k* gate dielectric MOSFETs,⁶ have also recently been invoked to interpret ion hopping⁷ and current fluctuations⁸ in RRAM devices. Building upon the RTN model developed for analyzing the conductive behavior of the gate dielectric^{6,9,18}

we herein statistically analyze RTN signals in contact-resistive random access memory (CR-RAM)^{10–12} to predict the electron-transport and resistive-switching characteristics, in relation to the traps in both the high-resistance state (HRS) and the low-resistance state (LRS).

II. CR-RAM RESISTANCE CHARACTERISTICS AND TEMPERATURE EFFECT

A contact-resistive RAM (CR-RAM) cell was demonstrated using a pure 90-nm CMOS logic process, in which the RRAM film was localized at the bottom of a contact hole. This structure allows a selected transistor to be easily connected to the switching resistor, giving a highly compact cell array and excellent compatibility for advanced CMOS logic technologies. The bottom-right inset in Fig. 1 outlines this 1T + 1R CR-RAM feature. RRAM stacking is realized by the TiN/TiON/SiO₂ located between the tungsten plug and N⁺Si. Previous studies of the CR-RAM cell,^{10,11} in which identical voltage polarities were applied during the set and reset operations, reported an extremely promising and reliable unipolar RRAM for NVM applications. However, the use of this unique CR-RAM cell is not limited to unipolar RRAM, thanks to its good bipolar switching characteristic, as demonstrated in Fig. 1, which make it a so-called nonpolar RRAM cell. The inset in Fig. 1 indicates the forward and reverse current directions. Therefore, the word line (WL) and the source line (SL) are biased by positive voltages, with a bit-line (BL) ground level indicating the forward operation. The reverse operation only needs to ground the SL with the WL and BL connected to positive voltages. The square symbol combines the forward set and the reverse reset to be the first operation group with $V_{WL} = 1.2$ V and $V_{WL} = 3$ V, respectively. Self compliance can be achieved with a smaller V_{WL} for set, whereas a higher V_{WL} ensures that there is enough reset current in the reverse direction.¹¹ Similarly, the group depicted by circles is realized by inverting the set and

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FIG. 1. (Color online) Bipolar switching characteristics of the CR-RAM cell can be demonstrated by combining forward set and reverse reset (or inverse) operations. During set, self-compliance can only be achieved by a forward operation, because of low voltage $V_{WL} = 1.2$ V, whereas a higher voltage $V_{WL} = 3$ V for a reverse set operation is inevitable. The inset shows the current directions in the CR-RAM cell during operation.

reset directions only. The reverse set voltage $V_{WL} = 3$ V, nevertheless, guarantees that the bit-line voltage (V_{BL}) is reliably passed to the N^+ floating node. However, a reverse set current, greater than the forward set current in the first group, is inevitable.

Carrier transport in RRAM films is normally explained in terms of a space charge limited current (SCLC) model, and the resistive switching behavior is attributed to trapping and detrapping processes in shallow trap states, likely to consist of oxygen vacancies.^{13–17} The $I \propto V$ (Ohmic behavior) correlation in the double-logarithmic I - V plot appears when there are fewer injected excess charge carriers than thermal free carriers inside the dielectric. As the number of injected carriers becomes comparable with that of thermal free carriers, carrier conduction becomes determined mainly by the shallow traps, giving rise to a square-law behavior. Therefore, the current can be written as the trap-free Mott-Gurney equation,

$$I = \frac{9}{8} \epsilon \mu \theta \frac{V^2}{L^3}, \quad (1)$$

where ϵ is the dielectric constant, θ is the density ratio of free to shallow trapped carriers, L is the film thickness, and μ is the carrier mobility. Figure 2 shows that the measured current, for both the HRS and LRS, is proportional to V^1 and (approximately) to V^2 for SL voltages smaller and greater than 0.3 V, respectively.¹⁷ It is therefore reasonable to assume that the conductive path in CR-RAM involves some kind of defects, such as interstitial or oxygen vacancies in disordered oxide thin films. The result of a high-temperature baking test, shown in Fig. 3(a), reveals that a sudden change in HRS levels occurs at a very high baking temperature of 250 °C. In contrast to the gradual loss of charge displayed in the retention behavior in conventional charge-storage flash memory, a sudden shift in the resistance level might indicate the release of trapped electrons. In addition, Fig. 3(b)

FIG. 2. (Color online) Logarithmic plot of the forward I - V curves for the HRS and LRS, fitted to the SCLC model. The current is proportional to $V^{1.04}$ in low-field region (Ohmic behavior) but increases to $V^{1.8}$ in the high-field region (Child).

compares the temperature dependence of the resistance levels of the CR-RAM in both the HRS and LRS. The normalized resistance decreases with increasing temperature in both states, where R_0 is the resistance at 0 °C. This implies that carrier conduction could be increased by the thermal energy, resulting in a negative temperature dependence of the resistance.

A conductive-filament model is also commonly used to explain the conduction and resistive switching behavior in a RRAM, as illustrated in Fig. 4. The filament provides a conductive path for electrons that can be broken by the heat produced by a large current. When switching from the LRS to the HRS, the I - V curve displays a decreasing gradient during the reset operation. A positive temperature dependence of the resistance is also expected, as shown in Figs. 4(d)–4(e). Consequently, the conductive-filament model cannot fully explain the observed CR-RAM conduction.³

FIG. 3. (Color online) (a) High-temperature baking tests of 250 °C and 150 °C are performed on the CR-RAM cell (solid and open symbols, respectively). Both the HRS and LRS at 150 °C are reliable for storage. A sudden change in the resistance level occurs only for the HRS at 250 °C. (b) The temperature dependence of the resistance levels of the HRS and LRS.

FIG. 4. (Color online) (a)–(c) The conductive filament path is ruptured in the presence of a current. The resistance therefore increases and reduces the gradient of the I - V curve in (d). (e) The temperature dependence of the resistance, with a positive gradient.³

III. RANDOM TELEGRAPH NOISE (RTN) ANALYSIS AND DISCUSSION

Occasionally, very large current fluctuations between distinctive resistance levels (theoretically due to electron trapping or detrapping) are detected during forward I - V measurements, as shown in Fig. 5. The first and second measurements demonstrate that the current can be either in the high or low level. Unlike the forward measurement, the reverse measurement shows a relatively smoother curve, which suggests that the on/off window disturbed by the current fluctuation can be alleviated by applying a reverse read, especially in integrated memory applications. In Fig. 6, both forward and reverse measurements display clear and stable RTN signals that fluctuate between two distinct current levels under DC bias condition, at 5°C and 25°C. The current fluctuations are clearly significantly reduced in the reverse measurement and the RTN signal fluctuations occur more frequently at 25°C for both the forward and the reverse measurements.

Some parameters must be defined here to analyze the data: The time spent in the high current level is denoted τ_c and corresponds to a trap being empty. Second, τ_e is defined as the time needed to fill the traps, resulting in the low current level. Third, ΔI is defined as the current difference between the two levels.

FIG. 5. (Color online) Distinct read current fluctuations measured during forward read in the HRS. A smoother curve is obtained for reverse read.

FIG. 6. (Color online) The RTN signals at the HRS have a larger amplitude under forward read than under reverse read. Increasing the temperature increases the frequency of the current fluctuations.

Comparisons of the reverse and forward measured RTN signals in the HRS are summarized in Fig. 7, and include some interesting features. First, although ΔI increases linearly with the read current in both read directions, the slope of ΔI , plotted as a function of the read current, is 14.4 times greater for forward read than for reverse read. This shows that the increment of the current amplitude fluctuations can be greatly suppressed in reverse read, thereby implying that it is a better read operation direction. Second, the relative current fluctuation, $\Delta I/I$, which remains relatively constant, reveals that electron trapping or detrapping results in the conduction path fluctuations of only 5–10% for reverse read, as opposed to 20–30% for forward read.

The WL bias voltage is another factor that can affect the capture/emission process of these traps. Figure 8 shows the dependence of the emission time τ_e and the capture time τ_c on the WL voltage. The dependence is weak and the small decrease in τ_c - τ_e could be due to measurement inaccuracy or to fringe fields affecting the traps in the CR-RAM film. Figure 8 also suggests that the possibility of the traps generating RTN signals in the SiO₂ gate dielectric can be discarded.

FIG. 7. (Color online) ΔI as a function of I for the CR-RAM cell in the HRS is linear for both (a) reverse and (b) forward read directions. However, the relative read current fluctuations $\Delta I/I$ remain relatively constant for both read directions.

FIG. 8. (Color online) The average lifetimes are independent of the WL voltage. The traps generating the RTN signals are therefore located inside the CR-RAM film instead of the SiO₂ gate oxide.

The above considerations lead us to believe that CR-RAM conduction is associated with traps inside the CR-RAM film. Figure 9(a) shows that the average lifetimes τ_e and τ_c , plotted as functions of voltage, exhibit a strong field-dependence in LRS. As a result, the electrons injected and captured from N⁺-Si, and then emitted via trapping sites, are strongly affected by the applied voltage. Figure 9(b) schematically describes carrier conduction in the CR-RAM film. Because the strong electric field applied in the set operation makes the electrons drop out of trapping sites, thereby depleting them, the band diagram becomes sharper in the region of the empty trapping sites, which greatly favors trap-assisted-tunneling transport. The average lifetimes τ_e and τ_c in the HRS are shown in Fig. 10(a) and exhibit a stronger field-dependence in electron capture. However, the emission time suggests a more significant thermally assisted process. The filling of traps in the TiO_xN_y layer after the reset operation raises the barrier height [see Fig. 10(b)], which decreases the voltage dependence of τ_e as shown in Fig. 10(a). Therefore, the electron can be emitted either thermally via path 1 or, as suggested by the weak voltage dependence, via path 2.

Based on the RTN model, the effective trap depth Z_{eff} inside the CR-RAM film can be well estimated from^{6,9}

FIG. 9. (Color online) (a) Both the average lifetimes, plotted as functions of voltage, exhibit a strong field dependence in the LRS. (b) Therefore, the energy band diagram in the LRS during forward read suggests that the electrons are captured from Si and emitted to the SL contact via the traps.

FIG. 10. (Color online) (a) Only τ_c exhibits a strong field dependence, while τ_e is expected to depend on a stronger thermally assisted process. (b) The energy band diagram, with respect to the HRS during forward read, implies that electrons can be emitted by thermionic emission (path 1) or tunneling (path 2).

$$\frac{d \ln \left(\frac{\tau_c}{\tau_e} \right)}{dV} = -\frac{q}{kT} Z_{eff}, \quad (2)$$

where the k is Boltzmann's constant, T is the equilibrium temperature and q is electronic charge. The effective trap depth extracted from forward measurements in both the HRS and LRS, is plotted as a function of the temperature in Fig. 11. As expected, Z_{eff} is independent of temperature in both states. Because a positive voltage is biased on the SL contact during the forward operation, a positive Z_{eff} clearly indicates that the depth is calculated from the N⁺-Si interface, whereas for a negative Z_{eff} it is calculated from the SL contact interface instead. The results show about 35% from N⁺-Si in the HRS and 15% from SL contact in the LRS, as shown in the inset.

The characteristics of the RTN signals analyzed by reverse measurement can also predict the trapping or detrapping behavior of the CR-RAM film. In a reverse measurement, a completely different energy barrier for the trap contributing the RTN signal produces a change in the field dependence of the lifetimes. Figure 12(a) shows the average lifetimes plotted as functions of the bit-line (BL) voltage in

FIG. 11. (Color online) The effective trap depth, Z_{eff} , extracted from the RTN model is independent of temperature. Trapping and detrapping occur near the N⁺-Si at the HRS but approaches the SL contact at the LRS.

FIG. 12. (Color online) (a) The average lifetimes, plotted as functions of the BL voltage during reverse read, show a weak voltage dependence for τ_e , while τ_c is nearly constant and smaller than τ_e in Fig. 10(a). Z_{eff} can also be extracted from the slope of the inset plot. (b) The energy band diagram, with respect to reverse read at the HRS, suggests the energy level of trapping sites is lower than the SL contact Fermi level, resulting in a shorter capture time. The weak voltage dependence of τ_e implies two emission paths.

the HRS, to allow a direct comparison with Fig. 10. First, τ_c in Fig. 12(a) depends weakly on the voltage and is always shorter than τ_e in Fig. 10(a) over the measured voltage range. This signifies that the trap energy level should be very adjacent to the Fermi level of the SL contact to achieve a faster capture and without a voltage dependence. However, the weak voltage dependence of τ_e suggests that emission still occurs by thermionic emission (path 1) and by tunneling (path 2), as depicted in Fig. 12(b). In addition, the positive gradient of $\ln(\tau_e/\tau_c)$ with respect to V_{BL} , shown in the inset, implies a negative Z_{eff} and indicates that the trap is near the N^+ -Si as a result of the reverse measurement. However, the Z_{eff} value of only 13% from N^+ -Si differs from the 35% value extracted from the forward measurement. This discrepancy should be considered from a microscopic point of view: the real voltage difference that affects the trap is transformed by the other trapped carriers or by the distortion of the energy barrier inside the CR-RAM film. In other words, to determine Z_{eff} precisely, the real voltage that affects the trap should be substituted in Fig. 12(a) for V_{BL} or V_{SL} . Nevertheless, the comparison of Figs. 10 and 12 also provides an important semiquantitative result.

IV. CONCLUSIONS

The observations of the instability of the HRS at a baking temperature of 250 °C and of negative temperature resistance widen the scope of discussion of electrical conduction

in CR-RAM films. Furthermore, the fitting of the SCLC model supports the hypothesis that carrier transport could be dominated by shallow traps that are most likely formed by the percolation spots or defects in the bandgap. The behavior of the RTN signals in a CR-RAM film further agrees with hopping conduction occurring via shallow traps, which trigger current fluctuations along the conductive path. Comparing the discrepancies in the behavior of average lifetimes between forward and reverse operations suggests how trapping or detrapping may affect the read current fluctuations in the CR-RAM film. Finally, extracting the parameters from the RTN model allows a better understanding of the trapping and detrapping behavior and of its distinctive characteristics.

ACKNOWLEDGMENTS

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research.

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