Evaluating the Effects of Physical Mechanisms on the Program, Erase and Retention in the Charge Trapping Memory

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***Abstract*—In this work, a new efficient simulation method with comprehensive physical models is developed to evaluate the performance of CTM at various biases, temperatures, and gate stack configurations. The dominant physical mechanisms on the P/E/R operations of CTM are clarified.**

Keywords : Charge Trapping Memory , Non-volatile Memory , Simulation of Programming /Erasing/Retention Characteristics

I. INTRODUCTION

SONOS type charge trapping memory (CTM) has emerged as one of the most competitive candidates for future non-volatile memory [1].Understanding the effects of physical mechanisms on the performances of CTM devices is needed. However, few works are concerned about modeling and simulation for CTM devices based on physical mechanisms [2-4]. In this work, we develop for the first time a self-consistent method to comprehensively simulate the process of carriers transport across multiple gate dielectric layers with trapping/de-trapping in charge storage layer included the general physical mechanisms and Monte-Carlo (MC) simulation tools.

The new simulator with the self-consistent method can simulate the program/erase/retention performances of CTM devices with various structures composed of multiple materials (even more than 3 layers) under arbitrary applied voltages. Based on the general physical models, the simulation can provide: (1) time evolution and spatial distribution of the potential, current and the energy loss in the multiple dielectric layers, (2) time evolution and spatial distribution of the trapped charge and localized charge in the charge storage layer, (3) time evolution of the threshold voltage during the program (P), erase (E) and retention (R) operations of CTM.

Based on the simulation, the impact of the mechanisms correlated with the process of the carriers in CTM on the P/E/R operation is evaluated. The results indicate that the impacts of different physical mechanisms on the P/E/R performances are complicated and parameters sensitive. Distinguishing the dominant mechanisms is critical to correctly and accurately evaluate the performance of CTM: (1) Trap assisted tunneling, thermally assisted tunneling, and recombination are critical to P/E operation; (2) Poole-Frenkel effect [9], thermally assisted tunneling, and localized charges are key factors to retention of CTM.

II. PHYSICAL MODELS AND SIMULATION METHOD

The processes of carriers transport across the multiple gate dielectric layers including trapping/de-trapping in the charge storage layer with comprehensive mechanisms are shown in Fig.1 and table 1. A self-consistent method is employed to refresh the barrier shape (Fig. 2) by solving Poisson equation during simulating on all type operations of CTM devices efficiently (Fig.3).

Under the framework of self-consistent method, the general physical models including tunneling, transport with relaxation, charge capture/excitation, recombination and localized carriers (Fig.1, Table 1) are implemented to determine the Program/Erase/ Retention (P/E/R) operation of CTM.

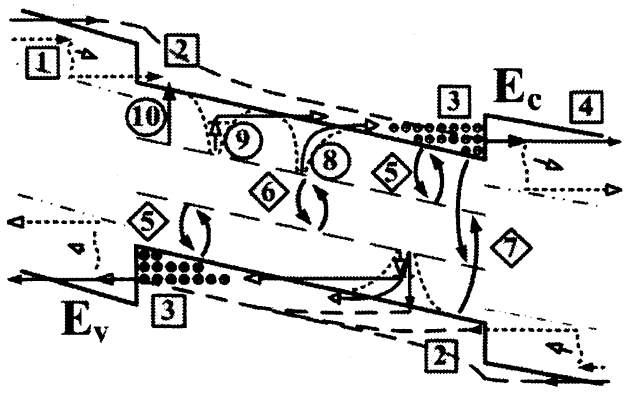

Figure 1. Fig.1 Illustration of the physical mechanisms of carriers transport across the multi-layer dielectrics (□) and charge trapping/de-trapping (○,◇) which are all implemented in this work. These fundamental physical models are used in simulating all types of operation (P/E/R).

TABLE I. DESCRIPTIONS OF IMPLEMENTED PHYSICAL MECHANISMS. INDICES ARE CORRESPONDING TO FIG. 1. THE MAIN MODELS AND THE MODEL PARAMETERS ARE LISTED IN TABLE 2. THE SIGN ⓞ CORRESPONDS TO THE PHYSICAL MECHANISMS WHICH ARE COMBINED TO BE IMPLEMENTED AND EVALUATED IN P/E/R OPERATIONS OF CTM DEVICES FOR THE FIRST TIME.

1	**Trap assisted tunneling (TAT).**
2	**Transport with relaxation (Relaxation).** Describe the carriers transport property in dielectrics with energy/momentum relaxation. Instead of ballistic.
3	**Localized electrons/holes. (e_{ACC}/h_{ACC}).** Carriers blocked by barriers which are formed by tunneling oxide and blocking oxide. DT/FN tunneling
4	**Trapping/Detrapping (Thermal excitation@).** Trapped carriers are excited to Ec only by thermal energy.
5	**Recombination between trapped charges.** The recombination occurs between trapped electrons and trapped holes.
6	**Recombination with free electrons/ holes.** The recombination occurs between electrons above Ec and trapped hole, holes below Ev and trapped electrons.
7	**Poole-Frenkel effect.**
8	**Thermally assisted tunneling (ThAT).** A two-step detrapping mechanism. First trapped electrons/holes could be thermally excited above the ground trap level in P-F effect's well and then tunnel though the barrier.

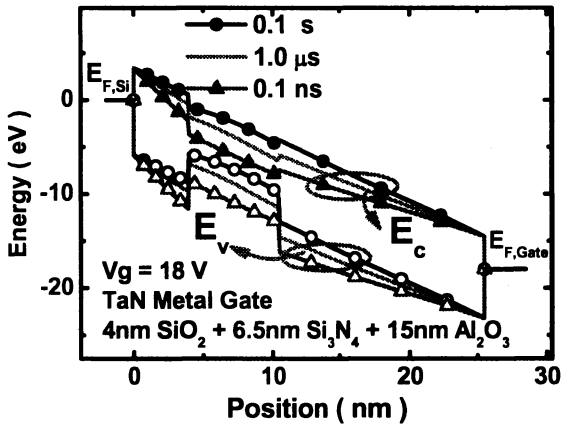

Figure 2. Time evolution of the band diagram of dielectric layers. Self-consistent simulation is shown obviously.

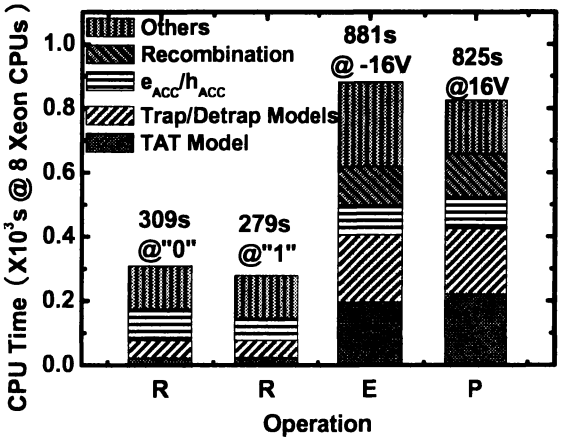

Figure 3. The components of CPU time in calculating the P/E/R characteristics of the same device. The simulation time span is 12 orders of magnitude, 60 points per decade.

The simulated results are verified and calibrated by the experimental results [1] as shown in Fig.4. The P-F coefficients are $3x10^{13}s^{-1}$ for electrons and $1x10^{13}s^{-1}$ for holes. Trap density are 2.6 and $1.1x10^{19}$cm-3 for electrons and holes respectively. Electron trap depth is 1.82eV, and 1.23eV for hole traps.

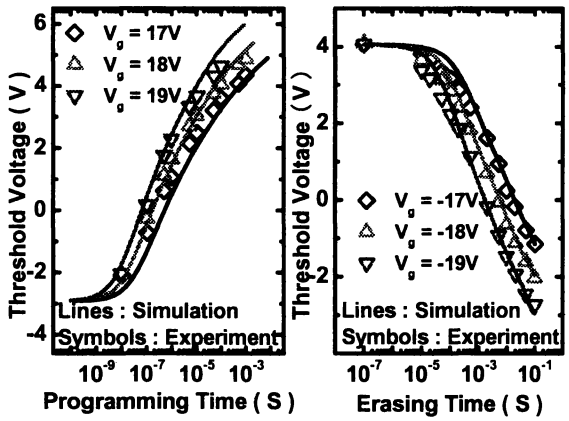

Figure 4. Verification of Simulation method as well as calibration of physical models. Symbols are the experimental data from Ref. [1], lines are simulation results.

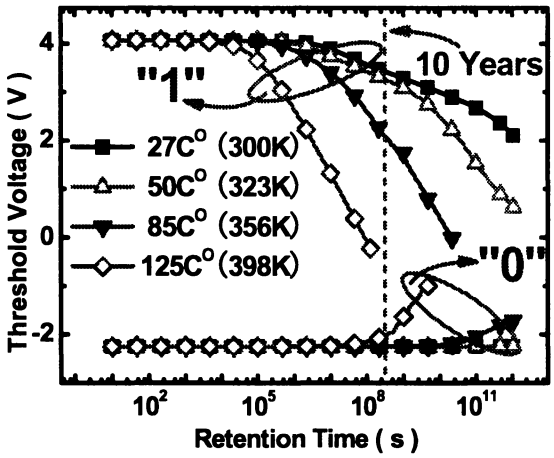

Figure 5. Retention characteristics of TANOS at different baking temperature.

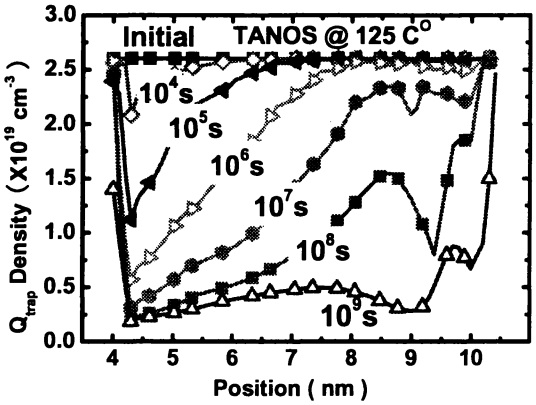

Figure 6. Time evolution of spatial distribution of trapped charge in charge trapping layer during retention at 125C°.

Tunnel effective masses are $0.42m_0/0.96m_0$ for electrons and holes. Figure 5 shows the retention characteristics under different baking temperatures. Different dominated charge loss mechanisms make the retention characteristics have different

slopes. The time evolution of trapped charges' spatial distribution in charge trapping layer (Fig. 6).

III. IMPACTS OF THE PHYSICAL MECHANISMS

The mechanisms' influence on the operation of CTM comes from two aspects: 1) carriers transport across the multiple dielectric layers, including FN tunneling, direct tunneling, Trap assisted tunneling (TAT). And the carriers transport across the dielectrics can be with energy/momentum relaxation instead of ballistic transport (Relaxation). 2) Charge trapping/de-trapping in charge storage layer including charge capture/thermal excitation, Poole-Frenkel effect (P-F), thermally assisted tunneling (ThAT) and recombination (REC). And the charges also can be localized in this layer (e_{ACC}/h_{ACC}).

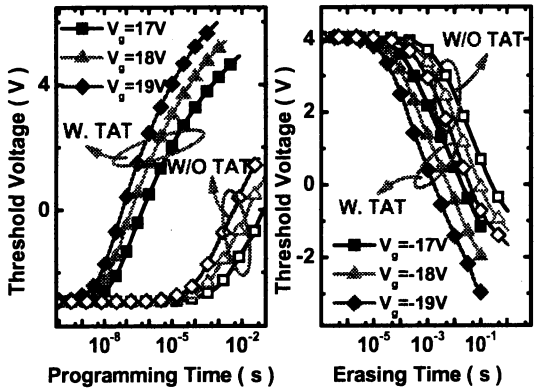

Figure 7. The impacts of trap assisted tunneling model (TAT) on programming / erasing characteristics of CTM.

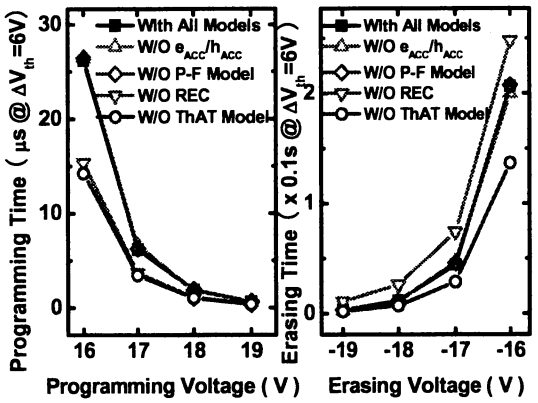

Figure 8. The effects of detrapping mechanisms and recombination on programming/erasing time of CTM.

Fig. 7 and 8 plot the impacts of the mechanisms on the P/E operation of CTM. TAT could dramatically accelerate the P/E operation because it increases the electron/hole tunneling current (Fig. 7). Though the other physical models do not have such predominant effects as TAT does on P/E characteristics, to better evaluate the performance of CTM, REC as well as ThAT has to be taken into account. Fig.9 and 10 show impacts of TAT, e_{ACC}/h_{ACC}, P-F and ThAT on the retention of CTM. As to retention characteristics, P-F affects a lot in both '1' and '0' states. The retention characteristic of zero state would be underestimated if hACC is ignored. Table 2 summarizes the impacts of all these physical mechanisms in P/E/R characteristics. TAT mechanism has the most influences on device performance. Poole-Frenkel is the main charge loss mechanism in charge trapping memory.

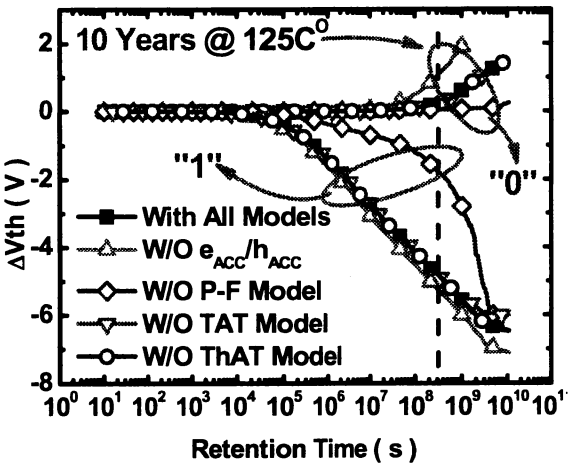

Figure 9. The retention comparison between all physical mechanisms which are considered to affect the retention performance of CTM.

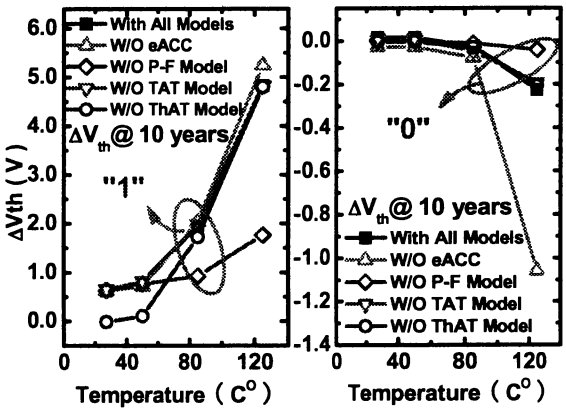

Figure 10. The temperature dependence of all physical mechansims during retention operation.

TABLE II. Summary of the impacts of physical models on CTM programming, erasing and retention performance. ↑ = increase, ↓ = decrease and -- = no influence

Mechanisms	Programming Speed	Erasing Speed	Retention "1"/"0"
TAT [1]	↓↓↓	↓↓	↓/↓
e_{ACC}/h_{ACC} [3]	—	—	↑/↑
Recombination ⑥⑦	↑↑	↓↓	N.A.
Poole-Frenkel ⑧	—	—	↓↓/↓↓
ThAT ⑨	↑↑	↑↑	—/—

IV. Performance of CTM with Advanced Structures

The simulation method can be used to simulate the CTM with advanced structures such as those employing complex configurations in blocking oxide and tunneling oxide. Fig. 11-12 show the comparisons between conventional and advanced structures. Though both "ONO" and "NON" type configurations of tunneling oxide could improve P/E performance while maintaining the retention capability, "ONO" type is one of the most promising candidate solutions.

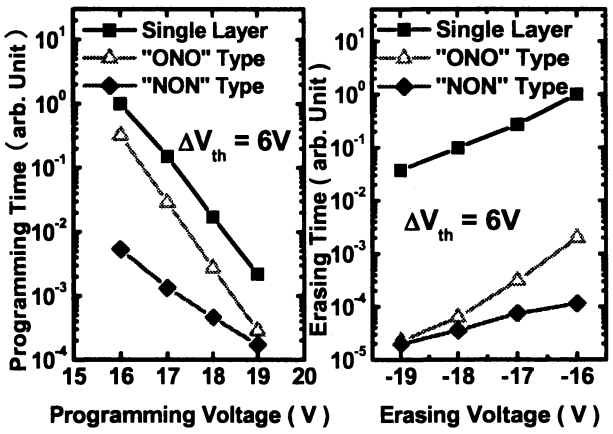

Figure 11. The comparison of programming / erasing characteristics between CTM with single tunneling oxide layer and stacked tunneling oxide.

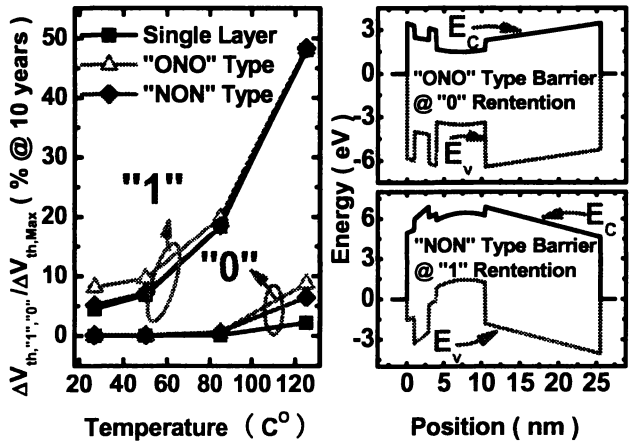

Figure 12. The retention characteristics of CTM with different tunneling oxide configuration. All configurations use the same total physical thickness of tunneling oxide and the same parameter set.

V. Summary

A new efficient simulation method with comprehensive physical models is developed to evaluate the performance of CTM at various biases, temperatures, and gate stack configurations. The dominant physical mechanisms on the P/E/R operations of CTM are clarified.

Acknowledgment

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