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Influence of Electron and Hole Distribution on 2T SONOS Embedded NVM

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***Abstract*—The influence of electron and hole (EH) distribution on two-transistor (2T) silicon-oxide-nitride-oxide-silicon (SONOS) embedded nonvolatile memory (eNVM) is investigated in terms of reliability. As PE (program/erase) cycles are repeated, it is observed that the electron distribution in the nitride layer becomes wider. It leads to the EH distribution mismatch, which degrades the reliability of 2T SONOS eNVM.**

***Index Terms*—2T SONOS, eNVM, mismatch, reliability**

I. INTRODUCTION

A two-transistor (2T) silicon-oxide-nitride-oxide-silicon (SONOS) memory cell has been considered as an attractive option to embedded nonvolatile memory (eNVM) due to its over-erase immunity and CMOS process compatibility [1]. Unlike a standalone SONOS NAND flash memory cell which uses Fowler-Nordheim tunneling for both program/erase (PE) operations, a 2T SONOS eNVM cell uses different PE mechanisms: channel hot electron injection (CHEI) for program operation and band-to-band-tunneling-induced hot-hole injection (BTBT-HHI) for erase operation. It is because low-voltage and high-speed operation are required for eNVM. However, because a 2T SONOS eNVM cell uses different PE mechanisms and charge trapping storage region, the mismatch between trapped electron and hole (EH) distribution can cause reliability issues. In the case of one-transistor (1T) SONOS eNVM cells shown in Fig. 1(a), the EH distribution mismatch has already been discussed elsewhere [2-4]. On the other hand, to the best of our knowledge, no EH distribution mismatch has been discussed so far in the case of 2T SONOS eNVM cells as shown in Fig. 1(b). This manuscript contributes to the reliability degradation of 2T SONOS eNVM cells induced by the EH distribution mismatch. Fig. 1(c) and (d) show their PE mechanisms by using vertical energy band diagrams. CHEI program is used to accelerate the electron trapping because interjunction between select gate (SG) and control gate (CG) potential decrease as voltage drop at the pinch-off region increases due to the

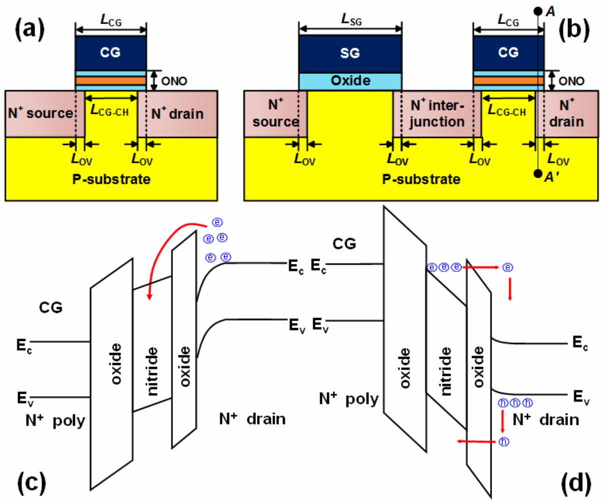

Fig. 1. Schematics of (a) 1T, (b) 2T SONOS eNVM cell. Vertical energy band diagram extracted from the *A-A'* line during, (c) program, (d) erase operation.

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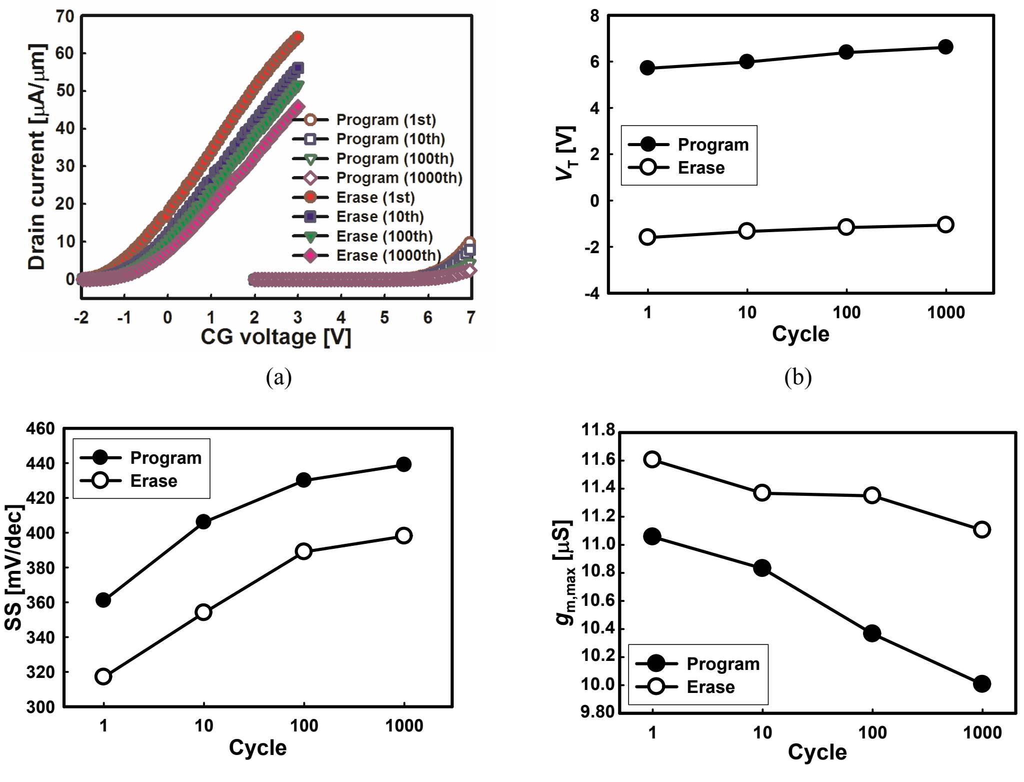


(a) (b)

(c) (d)

Fig. 2 (a) Measured I_{DS}-V_{GS}, (b) V_T, (c) SS, (d) $g_{m,max}$.

trapped electrons. However, CHEI program induces electron trapping widening, which leads to EH distribution mismatch. Thus, EH distribution mismatch on 2T cells is more severe than 1T cells. It is problematic that EH distribution mismatch is aggravated as PE cycles are repeated.

II. RESULTS AND DISCUSSION

Fig. 2 shows the measurement results of 100-nm 2T SONOS eNVM cell. Its PE conditions are summarized in Table 1. In the case of program operation, gate voltage is higher than drain voltage due to a thick ONO stack. It has been observed that the pile-up of electrons during each PE cycle results in threshold voltage (V_T) shift, subthreshold slope (SS) and maximum transconductance ($g_{m,max}$) degradation. In order to observe the mismatch between trapped EH distribution at each PE state, two-dimensional device simulation has been performed by using Synopsys Sentaurus [5]. Fig. 1(b) shows the simulated 2T SONOS cell structure. The select gate length (L_{SG}) is 200 nm. Control gate length (L_{CG}) is 100 nm. Gate overlap length (L_{OV}) is 10 nm. ONO stack thickness is 6/8/4.5 nm respectively. Graded source/drain junction doping gradient from gate edge is 5 nm/dec. CHEI and BTBT-HHI have been used for program and erase operation, repectively as shown in Table 1. Read operation has been performed by exchanging source and drain regions with V_D fixed at 1 V. It should be noted that model parameters such as effective tunneling mass are adjusted to make one PE cycle in device simulation correspond to 200 PE cycles in measurement for short simulation time and higher convergence.

Table 1. Program/erase conditions

Operation	V_{SG}	V_{CG}	V_D	V_S	Time
Program	5.0 V	7.0 V	4.5 V	0 V	20 μs
Erase	5.0 V	0 V	4.5 V	Float	100 ms

Fig. 3 and show the simulated profiles of trapped electrons and holes during the first PE cycle. Narrow electron distribution is related to maximum lateral electric field position of CG during program. Because interjunction has floating potential, decreased voltage drop at the pinch-off region by trapped electron makes interjunction potential decrease as shown in Fig. 4(a).

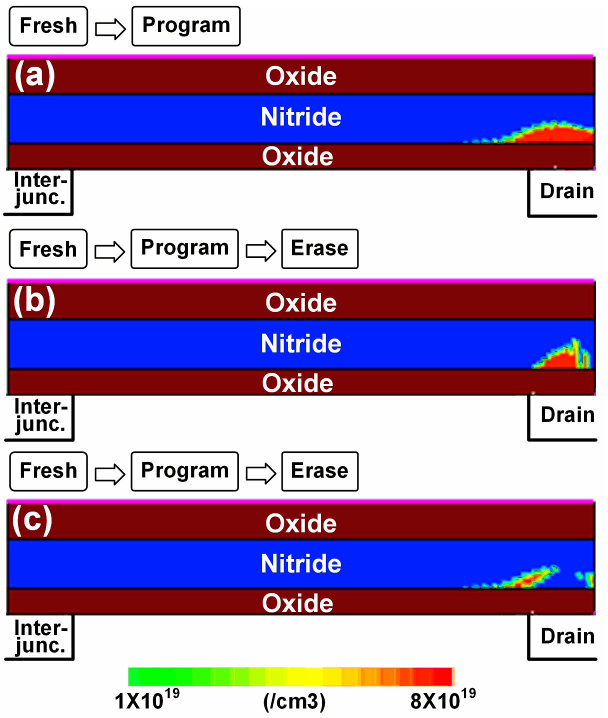
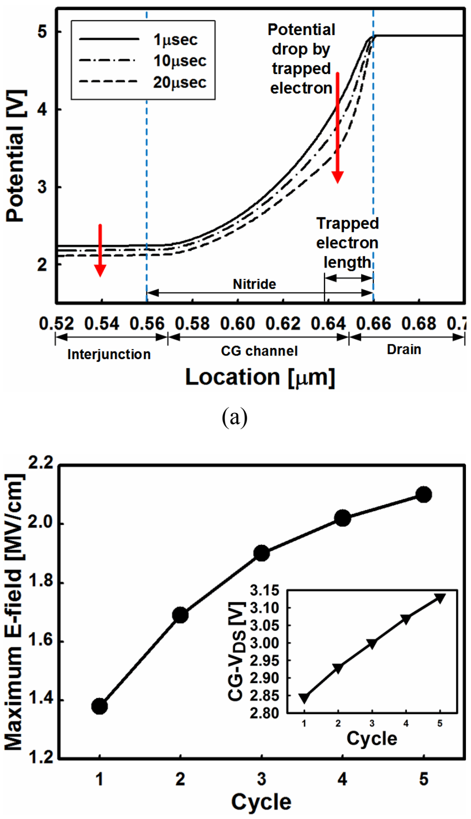


Fig. 3. (a) Simulated trapped electron distribution in CG after the first program operation, (b) Simulated trapped hole distribution in CG after the first erase operation, (c) Simulated trapped electron distribution in CG after the first erase operation.

Thus, the electron trapping is accelerated by increased maximum lateral electric field during program operation. After the first PE cycle, some trapped electrons still remain as shown in Fig. 3(c). This mismatch causes the voltage applied to the CG (CG-V_{DS}) and maximum lateral electric field increase as PE cycles are repeated. The inset of Fig. 4(b) shows the CG-V_{DS} versus the PE cycle number. The maximum lateral electric field increases as PE cycles are repeated as shown in Fig. 4(b). Program acceleration becomes more severe as the PE cycle repeated. Thus, EH distribution mismatch of 2T cells is more severe than that of 1T cells as PE cycles are repeated as shown in Fig. 5. Fig. 6 shows that the V_T shift, SS and $g_{m,max}$ of 2T cells are degraded as the local pile up of electrons increases. First, V_T degradation is explained by the increase of source-to-channel potential barrier height due to the EH mismatch. When the electrons are trapped in the nitride layer over the channel, the channel energy band under the trapped electrons tends to shift upward [7]. Second, SS degradation is related to the channel surface which is controlled by the gate voltage [8-10]. In the subthreshold region, the surface channel



(a)

(b)

Fig. 4. (a) Simulated potential during the first program, (b) Simulated maximum lateral electric field during five PE cycles. The inset shows that V_{DS} of CG increases during five PE cycles.

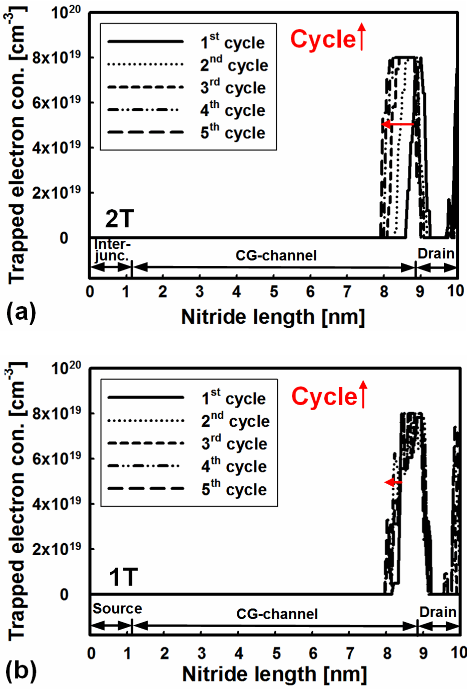


Fig. 5. Simulated electron distribution in the erased state as PE cycles are repeated for (a) a 2T, (b) 1T cell.

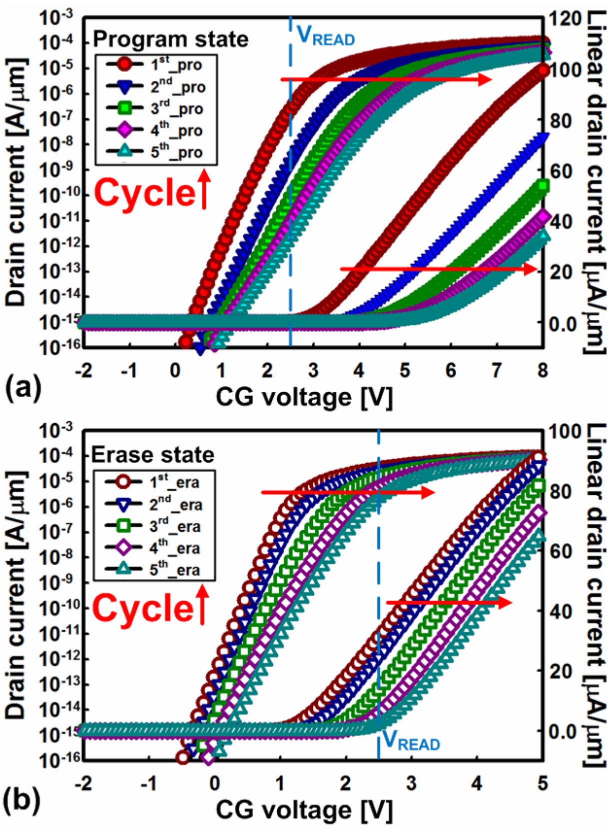


Fig. 6. Simulated I_{DS}-V_{GS} during five PE cycles (a) when programmed, (b) when erased.

under the trapped electrons is depleted and the rest of the surface channel is inverted, which means poor coupling between the gate and surface channel. Finally, $g_{m,avr}$ degradation is related to parasitic source resistance. When electrons are trapped over the graded junction, the electron concentration of graded junction decreases.

III. CONCLUSIONS

The influence of EH mismatch on 2T SONOS eNVM has been discussed for the first time. During the program operation of 2T cells, electron distribution is wider than hole distribution due to the accelerated electron trapping. Thus, EH distribution becomes worse as PE cycles are repeated. It is also observed that the 2T SONOS eNVM cells are more vulnerable to the EH distribution mismatch than 1T ones.

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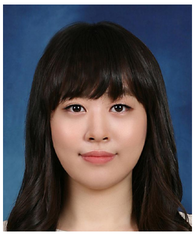

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