V_t Retention Distribution Tail in a Multitime-Program MLC SONOS Memory Due to a Random-Program-Charge-Induced Current-Path Percolation Effect

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***Abstract*—A V_t retention distribution tail in a multitime-program (MTP) silicon–oxide–nitride–oxide–silicon (SONOS) memory is investigated. We characterize a single-program-charge-loss-induced ΔV_t in NOR-type SONOS multilevel cells (MLCs). Our measurement shows the following: 1) A single-charge-loss-induced ΔV_t exhibits an exponential distribution in magnitudes, which is attributed to a random-program-charge-induced current-path percolation effect, and 2) the standard deviation of the exponential distribution depends on the program-charge density and increases with a program V_t level in an MLC SONOS. In addition, we measure a V_t retention distribution in a 512-Mb MTP SONOS memory and observe a significant V_t retention tail. A numerical V_t retention distribution model including the percolation effect and a Poisson-distribution-based multiple-charge-loss model is developed. Our model agrees with the measured V_t retention distribution in a 512-Mb SONOS well. The observed V_t tail is realized mainly due to the percolation effect.**

***Index Terms*—Model, percolation, silicon–oxide–nitride–oxide–silicon (SONOS), V_t retention distribution.**

I. Introduction

Silicon–oxide–nitride–oxide–silicon (SONOS) Flash memory has received much interest because it offers better performance with small cell size, fast program/erase, and memory retention improvement than a floating-gate (FG) Flash memory [1] cells with a vertical gate [2], [3] have been considered as a promising candidate for a 3-D nonvolatile memory in terabit storage applications. However, as the scaling of the SONOS technology advances aggressively, significant variations of V_t retention loss in SONOS cells are observed because of a reduced number of stored charges [4]. For a technology node beyond 45 nm, only tens of electrons are stored in each program level of a multilevel cell (MLC) SONOS. A single-charge loss would induce a large variation in read current and sometimes result in a read failure. Two kinds of single-charge phenomena in a Flash cell have been reported. One is the switching of a read current between two current levels, referred to as random telegraph noise (RTN), due to single-charge emission and capture at an interface oxide trap. The other is discrete program-charge retention loss, which is manifested by a stepwise increase of read current versus retention time [4]. The RTN amplitudes in FG Flash and SONOS cells have been studied extensively [5]. The RTN amplitudes are found to follow an exponential distribution approximately in both FG and SONOS cells due to a current-path percolation effect [6], [7]. As for a single-program-charge-loss-induced ΔV_t, SONOS and FG Flash cells, however, exhibit different characteristics. In an FG cell, program charges are stored in a conducting and equipotential FG. Thus, each program-charge loss has the same weight and contributes the same ΔV_t [8]. Unlike those in an FG cell, program charges in a SONOS are stored randomly and discretely in an insulating silicon nitride layer. The current percolation paths in a channel are therefore affected by random placement of nitride program charges [4], [5], [9]. A program-charge loss at different positions of a nitride may result in a large difference in ΔV_t due to a percolation effect. In this paper, we characterize a single-program-charge-loss-induced ΔV_t in different program levels in a NOR-type MLC SONOS. An RTN-induced ΔV_t distribution is also characterized for comparison.

In addition, we measure a V_t distribution in a 512-Mb SONOS before and after 1000-h retention. A significant postretention V_t tail is observed. To examine the cause of the V_t tail bits, we develop a numerical V_t distribution model based on the current-path percolation effect and a Poisson-distribution-based multiple-charge-loss model [10]. An analytical description of the V_t tail bit distribution is derived. We evaluate the tail bit distributions from the percolation effect and multiple-charge loss, respectively. By using the model, we simulate a V_t tail in different program levels of an MLC SONOS.

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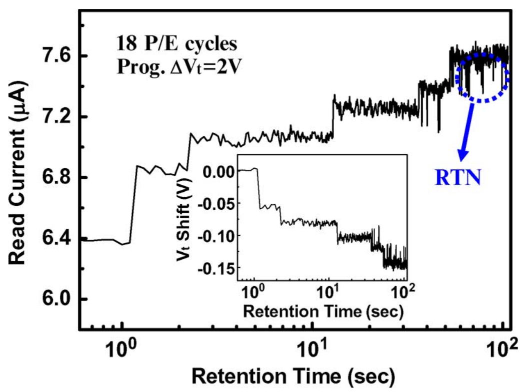

Fig. 1. Read current versus cumulative retention time in a P/E cycle SONOS. The measurement consists of two alternating phases, namely, retention phase and read phase. To accelerate program-charge loss, a negative gate voltage of -5 V was applied in the retention phase. The inset shows a corresponding V_t retention trace.

II. Single-Program-Charge-Loss-Induced ΔV_t

NOR-type SONOS cells in this work are fabricated with a 0.1-μm technology. The gate width (W) and length (L) are $W/L = 0.1$ μm/0.14 μm. The thicknesses of top oxide, silicon nitride, and bottom oxide are 7, 6, and 5.5 nm, respectively. Channel hot electron program and band-to-band hot hole erase are employed with a reverse read scheme [11]. The program and erase bias conditions are $V_g/V_s = 8.5$ V/4.2 V and $V_g/V_s = -7$ V/4 V, respectively. To characterize a single-program-charge-loss-induced ΔV_t, our measurement consists of two alternating phases, namely, retention loss phase and read phase. The V_d in read phase is 1.5 V. To accelerate program-charge loss, a negative gate bias of -5 V was applied in the retention phase. Fig. 1 shows the evolution of a read current with cumulative retention time in an 18-P/E-cycle SONOS cell. Discrete nitride-program-charge loss is clearly observed, which is manifested by sudden jumps in a read current. Each current jump is realized due to a single-program-charge loss [4]. Two-level RTN is also noticed in the figure. A corresponding V_t retention trace is plotted in the inset of the figure, which is obtained from the measured current divided by a transconductance at the read current. The reason why we measure a read current rather than a threshold voltage directly is that the current measurement has a better resolution. It should be mentioned that the magnitude of a single-charge-induced ΔV_t varies from program charge to program charge. This feature is different from an FG Flash cell, where each program-charge loss should induce the same V_t shift. Moreover, we measure V_t retention traces at three different P/E cycles. The result is shown in Fig. 2. Because the placement of program charges changes at a different P/E cycle, the V_t retention trace varies from cycle to cycle, suggesting that current percolation paths in program state are determined by the injected program charges. An average of V_t retention traces in 40 devices is shown in Fig. 3. The $\log(t)$ dependence of V_t retention loss in Fig. 3 is consistent with a Frenkel–Poole charge emission model [12].

We collect all the V_t jumps from more than 80 retention traces in different P/E cycles in a total of 40 devices. The cumulative probability distribution of the ΔV_t magnitude is shown in Fig. 4 in three program levels ("10," "01," and "00," which are defined as program V_t windows of 1, 2, and 3 V, respectively.). Data points with ΔV_t less than 5 mV are not drawn here because of the resolution of the measurement. In Fig. 4, we find the following: 1) The ΔV_t magnitude distribution in each program level can be approximated by an exponential function $f(\Delta V_t) = \exp(-\Delta V_t/\sigma)/\sigma$, and 2) the σ increases with a program V_t level. To explain the reason for an increasing σ with a program V_t level in a SONOS cell, we perform a 2-D numerical device simulation by ISE-TCAD for the three program V_t levels. The read V_d is 1.5 V, and the V_g is

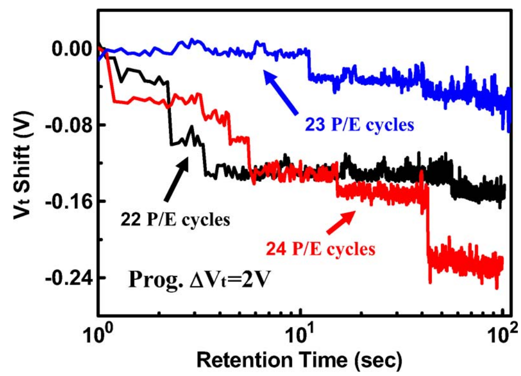

Fig. 2. Program V_t retention traces as a function of cumulative retention time at three consecutive P/E cycles (22, 23, and 24 cycles).

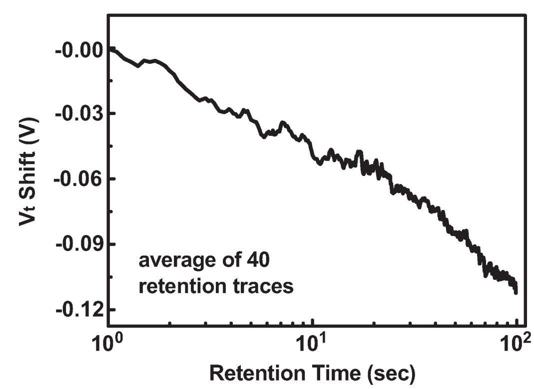

Fig. 3. Average of V_t retention traces in 40 SONOS cells. A $\log(t)$ retention time dependence is observed. A negative gate voltage of -5 V was applied in retention for accelerating charge loss.

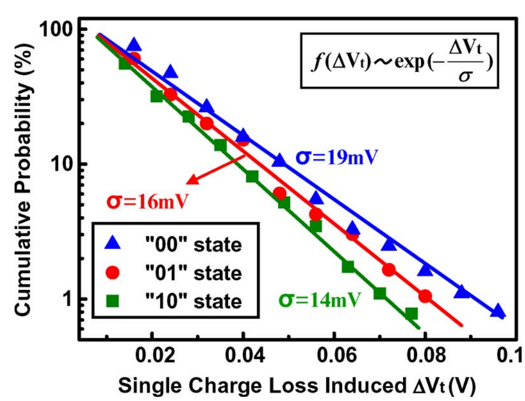

Fig. 4. Cumulative probability distribution of a single-program-charge-loss-induced ΔV_t in an MLC SONOS. The program V_t levels are $\Delta V_t = 1$ V for "10," $\Delta V_t = 2$ V for "01," and $\Delta V_t = 3$ V for "00." The distribution at each program level is measured at $V_d = 1.5$ V and $I_d = 6$ μA. The gate overdrive is about 0.6 V.

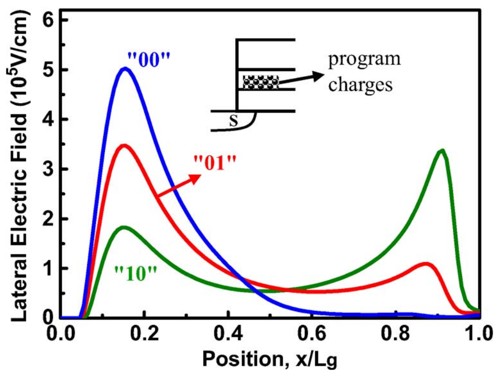

Fig. 5. Calculated channel lateral field distributions in "10," "01," and "00" states. The read V_d is 1.5 V, and the read V_g is chosen to keep the read current at 6 μA. The CHE program charge has a uniform distribution in a 15-nm region above the source junction, as shown in the figure.

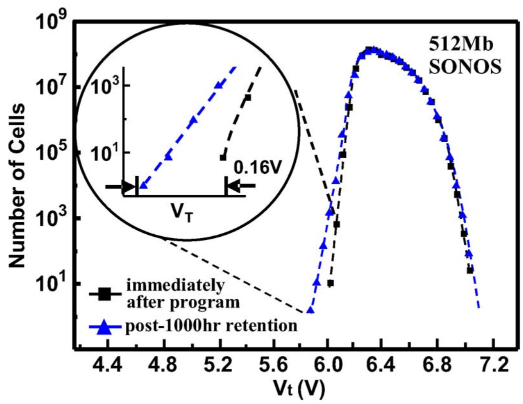

Fig. 6. Measured V_t distributions in a 512-Mb NOR-type MTP SONOS memory immediately after program and after 1000-h retention. No gate stress voltage was applied in retention. A postretention V_t distribution tail is highlighted.

adjusted to keep the read current level at 6 μA. The simulated lateral electric field profiles are shown in Fig. 5. The highest V_t level has the largest lateral electric field E beneath a program-charge region (i.e., near the source junction in Fig. 5). From a first-order approximation, a single-charge-loss-induced ΔI_d is proportional to $q\mu E$. Thus, a program-charge loss at a higher program V_t level results in larger ΔV_t and σ because of a larger E under a program-charge region.

In addition to single device data, we measure a V_t retention distribution in a 512-Mb SONOS memory. The program V_t distributions immediately after program and after 1000-h retention are shown in Fig. 6. The program window is 2 V, and the P/E cycle number is about ten [multitime program (MTP)]. In Fig. 6, we find that the main part of the V_t distributions before the retention and that after the retention match very well, suggesting that the majority of the cells do not have program-charge loss. Aside from the main distribution, we clearly observe a tail in the postretention V_t distribution, which is highlighted in Fig. 6. The spread of the V_t tail is about 0.16 V.

We further measure a postretention V_t shift by bit-by-bit tracking in an 8-Mb MTP SONOS array. The cumulative probability distributions of the V_t shift are plotted in Fig. 7 at two retention times: 168 and 1000 h. Two points should be noted. First, the tail of the V_t shift can be well fitted by an exponential

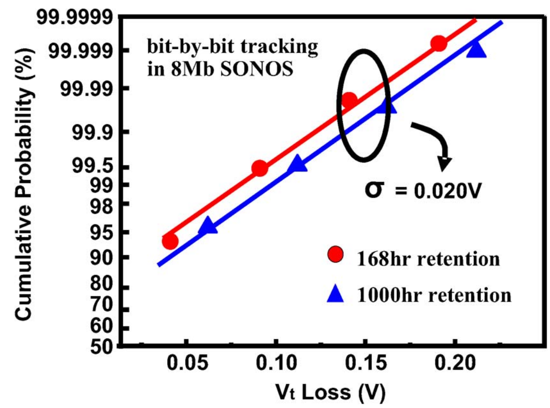

Fig. 7. Cumulative probability distributions of V_t retention loss at two retention times (168 and 1000 h) in an 8-Mb MTP SONOS are measured by bit-by-bit tracking. The solid lines represent an exponential distribution with a σ value of 0.020 V.

distribution (solid lines in Fig. 7), and the extracted σ value is about 0.02 V. Second, the V_t loss tail increases with retention time, which provides evidence that the measured ΔV_t loss tail is caused by program-charge loss rather than RTN. Furthermore, we would like to make a note about the comparison of RTN amplitudes and a program-charge-loss-induced ΔV_t. We measure RTN amplitudes in 30 SONOS cells. The σ value of RTN is about $\Delta V_t = 12$ mV, which is significantly smaller than the σ value of a program-charge-loss-induced ΔV_t. The reason is that RTN traps in MTP SONOS cells are randomly distributed in the channel and only a small part of the RTN traps are in the program-charge region of about 15 nm [13]. As pointed out earlier, a charge loss in a high-lateral-field region (program-charge region), whether an RTN charge or a program charge, yields a larger ΔV_t. Thus, most of the RTN-induced ΔV_t values are small. This can explain why program-charge loss rather than RTN dominates the V_t retention tail in a 512-Mb SONOS memory.

III. Modeling of V_t Retention Distribution

In this section, a numerical model to simulate a V_t retention distribution is developed. Our model includes a program-charge-induced percolation effect and a Poisson-distribution-based multiple-charge-loss model. The distribution function of a single-program-charge-loss-induced ΔV_t is expressed as

$$f(\Delta V_t) = \frac{1}{\sigma}\exp\left(-\frac{\Delta V_t}{\sigma}\right) \tag{1}$$

where σ is an average value of ΔV_t and also the standard deviation of the distribution. Assume that $g(V_t)$ is a program V_t distribution immediately after program, which can be obtained from measurement. The V_t distribution after a single-charge loss is calculated from a convolution integral of $f(\Delta V_t)$ and $g(V_t)$, i.e.,

$$f(\Delta V_t) * g(V_t) \equiv \int f(\Delta V_t) g(V_t + \Delta V_t) d\Delta V_t \tag{2}$$

where the symbol $*$ presents a convolution integral. Therefore, the postretention V_t distribution $h(V_t)$ can be derived from (2)

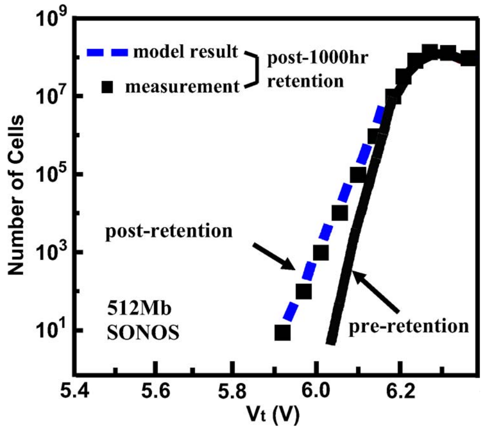

Fig. 8. Modeled and measured V_t distributions after 1000-h retention. The σ value used in the model is 0.020 V. The λ value is equal to 0.1. The integration interval of the convolution integral is 0.625 mV. The preretention distribution is also plotted as a reference.

and weighted by the probability of a Poisson distributed number of program-charge loss $P_\lambda(n)$, as described in the following:

$$P_\lambda(n) = \frac{e^{-\lambda}\lambda^n}{n!}. \tag{3}$$

$P_\lambda(n)$ denotes the probability of n-program-charge loss in a cell, and λ is an average number of charge losses in a cell. The postretention V_t distribution finally can be expressed as

$$h(V_t) = P_\lambda(0)g(V_t) + P_\lambda(1)f(\Delta V_{t1}) * g(V_t) + P_\lambda(2)f(\Delta V_{t2}) * (f(\Delta V_{t1}) * g(V_t)) + \cdots \tag{4}$$

where the first term $P_\lambda(0)g(V_t)$ represents the cells without charge loss and the second term $P_\lambda(1)f(\Delta V_{t1}) * g(V_t)$ and the third term $P_\lambda(2)f(\Delta V_{t2}) * (f(\Delta V_{t1}) * g(V_t))$ represent a single-charge loss and a two-charge loss, respectively. Other terms for loss of more than two charges can be expressed in a similar way. The model is used to simulate a V_t retention distribution in a 512-Mb MTP SONOS. In the simulation, σ is obtained from measurement (20 mV in Fig. 7), and λ is treated as a fitting parameter. The measurement and model results are shown in Fig. 8. Our model fits the measured distribution well with $\lambda = 0.1$. This small value of λ is reasonable in an MTP operation. In order to compare the contributions from multiple-charge loss and from the percolation effect to the V_t tail, we calculate the single-, two-, and three-charge-loss-induced V_t retention tails according to (4). The result is shown in Fig. 9. The single-charge loss dominates a postretention V_t tail because a single-charge-loss probability is much larger than the probability of multiple-charge loss. This result reveals that the V_t retention loss tail in a SONOS memory is mainly attributed to a random-program-charge-induced percolation effect.

In addition, we simulate the percolation-effect-induced V_t retention tail in different program levels of an MLC SONOS memory. The parameter λ is assumed to be proportional to a program V_t window as a first-order approximation. The reason is that an average number of charge losses (λ) should be dependent on the number of stored charges in a cell and the latter is proportional to a program window. For simplicity, we assume that each program level has the same initial program

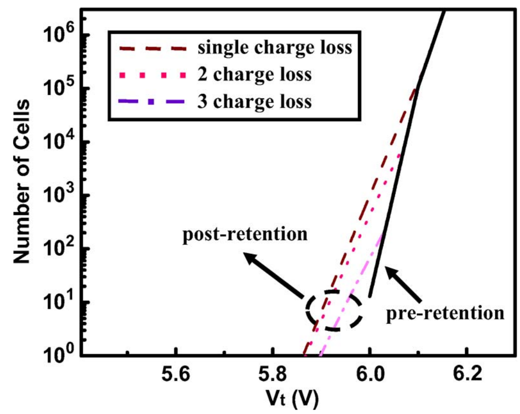

Fig. 9. Calculation of single-, two-, and three-charge-loss-induced V_t retention tails. The V_t retention distribution tail is mainly contributed by the percolation effect.

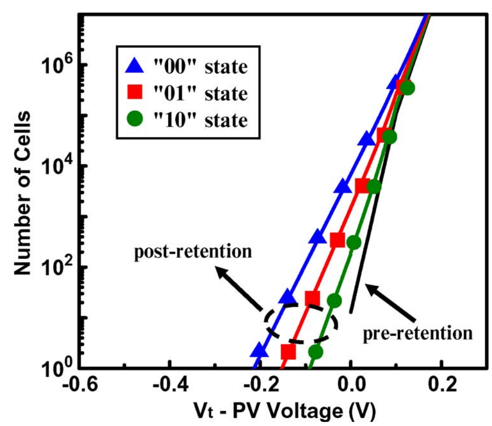

Fig. 10. Calculated V_t retention distribution tail in different program levels of an MLC SONOS. The V_t retention tail is plotted with reference to a PV voltage.

V_t distribution $g(V_t)$. The simulation result is plotted in Fig. 10 with reference to a program verify (PV) voltage. The highest program level ("00") apparently has the largest V_t retention tail due to a larger percolation effect, i.e., a larger σ. The large V_t tail may cause a read error in an MLC and requires the use of an error code correction technique [14].

IV. CONCLUSION

We observe and characterize discrete program-charge loss in a SONOS cell. A single-program-charge-loss-induced ΔV_t exhibits approximately an exponential distribution due to a random-program-charge-induced percolation effect. The program-charge-loss-induced ΔV_t is larger than an RTN-induced ΔV_t in a NOR-type SONOS. A V_t retention distribution model including the percolation effect and Poisson-distribution-based multiple-charge-loss model has been developed. Our model can simulate a postretention V_t distribution in an MTP SONOS memory. Our simulation confirms that the observed postretention V_t distribution tail is attributed to the percolation effect, a unique characteristic in a SONOS memory. Our study further shows that the V_t distribution tail increases with a program V_t level in a NOR-type MLC SONOS. The percolation effect and the V_t loss tail are expected to be more pronounced in further scaling of the SONOS technology.

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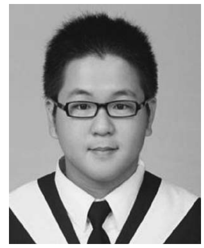

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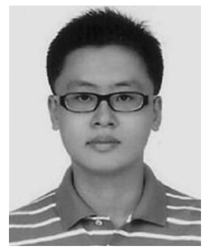

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Dr. Lu is a Fellow of the American Physical Society. He was the recipient of the IEEE Millennium Medal and the Most Prestigious Semiconductor R&D Award in Taiwan from Pan Wen Yuan Foundation and the highest honor prize, i.e., the National Science and Technology Achievement Award, from the Prime Minister of Taiwan for his leadership and achievement in the Submicron Project.