A New Statistical Model for SILC Distribution of Flash Memory and the Effect of Spatial Trap Distribution

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***Abstract*— A new statistical model accurately reproducing the result of the Monte-Carlo (MC) simulation is proposed for the analysis of the SILC distribution of flash memory. From the pre-calculated probability density distributions (PDD) of the current through one multi-trap (1-trap and 2-trap) path, the current PDD of the cell is obtained using the convolution theorem and compared with the result of MC simulation. Current PDD of the cell is found to be very sensitive to the spatial distribution of traps.**

I. Introduction

Charge retention is one of the most important reliability issues of flash memory. The retention failure is attributed to the large SILC through the multi-trap paths in the oxide stressed by program/erase (P/E) cycling [1]–[3]. A number of models have been proposed to analyze the trap generation statistics and predict the lifetime of memory in the aspect of retention [4]–[6]. Also, the dependence of SILC distribution on trap volume density, energy and capture cross-section was investigated by MC simulations whose sampling numbers were 10^7 [3]. Most of models, however, assumed that the traps were distributed uniformly in the oxide and no result has been reported for the effect of spatial distribution of traps on the SILC distribution of the cell.

Driussi, *et al.* [7] showed that the current PDD of the cell having only 1-trap paths can be obtained from the average number of traps in the cell and the current PDD of one 1-trap path.

In this paper, we generalize the model suggested by Driussi, *et al.* [7] to calculate the current PDD of the cell having not only the 1-trap paths but also the multi-trap paths consisting of two or more traps. Since MC simulation is very time consuming, the proposed model is used to study the effect of spatial distribution of oxide traps on the SILC distribution.

II. Statistical Model

Since the oxide traps have been believed to be randomly generated by the electrical stress [8], we assume that the trap generation follows the Poisson's statistics. Therefore, the traps generated during the stress are not correlated one another.

If there are $\mathrm{n_k}$ k-trap paths, where the k-trap path is defined as the conductive path consisting of k traps in the oxide, the current PDD $f_k(I|n_k)$ of the cell having $\mathrm{n_k}$ k-trap paths can be obtained as the convolution of the current PDD $f_k(I|n_k-1)$ of the cell having ($\mathrm{n_k}$-1) k-trap paths and the current PDD $f_k(I|1)$ of the cell having only one k-trap path.

$$\begin{aligned} f_k(I|n_k) &= f_k(I|n_k-1) * f_k(I|1) \\ &= \int_0^I f_k(I|n_k-1) f_k(I-I'|1)\mathrm{d}I'. \end{aligned} \quad (1)$$

Since the current PDD $f_k(I|n_k-1)$ can be also obtained as the convolution of $f_k(I|n_k-2)$ and $f_k(I|1)$, the current PDD $f_k(I|n_k)$ of (1) can be rewritten as

$$f_k(I|n_k) = \underbrace{f_k(I|1) * \cdots * f_k(I|1)}_{n_k} * f_k(I|0) \quad (2)$$

where $f_k(I|0)$ is the current PDD of the cell having no k-trap paths. If the current fluctuation of the cell, where no conductive paths are formed during the stress, is negligibly small, $f_k(I|0)$ can be expressed as

$$f_k(I|0) = \delta(I) \quad (3)$$

where $\delta(I)$ is the Dirac delta function of current I. Then, the current PDD $f_k(I|n_k)$ can be obtained from the convolution of $f_k(I|1)$ by $\mathrm{n_k}$ times.

Let $F_k(\omega|n_k)$ and $Q_k(\omega)$ be the Fourier Transform of the current PDD $f_k(I|n_k)$ and $f_k(I|1)$, respectively. Using the convolution theorem, $F_k(\omega|n_k)$ can be written as

$$F_k(\omega|n_k) = Q_k(\omega)^{n_k}. \quad (4)$$

By summing over $\mathrm{n_k}$ from 0 to ∞ for the current PDD's $f_k(I|n_k)$ weighted by the conditional probability $p(n_k|k)$ of the cell having $\mathrm{n_k}$ k-trap paths, the current PDD $f_k(I)$ of the cell having k-trap paths is obtained as

$$f_k(I) = \sum_{n_k=0}^{\infty} f_k(I|n_k)p(n_k|k). \quad (5)$$

Let $F_k(\omega)$ be the Fourier Transform of the current PDD $f_k(I)$. From (4) and (5), $F_k(\omega)$ can be written as

$$\begin{aligned} F_k(\omega) &= \sum_{n_k=0}^{\infty} F_k(\omega|n_k)p(n_k|k) \\ &= \sum_{n_k=0}^{\infty} Q_k(\omega)^{n_k} \frac{\lambda^{n_k}}{n_k!} e^{-\lambda_k} \\ &= e^{\lambda_k(Q_k(\omega)-1)} \end{aligned} \quad (6)$$

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where λ_k is the average number of k-trap paths in the cell and the conditional probability $p(n_k|k)$ is obtained from the Poisson's statistics with the average number λ_k.

Since there can be many different types of conducting paths in the cell, e.g. 1-trap path, 2-trap path, etc., the current PDD $f(I)$ of the cell can be obtained as the convolution of the current PDD of each conducting path as

$$\begin{aligned} f(I) &= f_1(I) * f_2(I) * \cdots * f_k(I) * \cdots \\ &= \left[\sum_{n_1=0}^{\infty} f_1(I|n_1)p(n_1|1)\right] * \left[\sum_{n_2=0}^{\infty} f_2(I|n_2)p(n_2|2)\right] \\ &\quad * \cdots * \left[\sum_{n_k=0}^{\infty} f_k(I|n_k)p(n_k|k)\right] * \cdots . \end{aligned} \tag{7}$$

Using the convolution theorem, $f(I)$ can be rewritten as

$$f(I) = \mathcal{F}^{-1}\left\{\prod_{k=1}^{\infty} e^{\lambda_k(Q_k(\omega)-1)}\right\} \tag{8}$$

where $\mathcal{F}^{-1}$ is the inverse Fourier Transform.

III. Average Number λ_k and Current PDD $f_k(I|1)$ of One k-Trap Path

In this paper, we restrict our concern to the 1-trap path and 2-trap path because the 2-trap conductive path has been known to be attributed to the anomalous SILC of fail bits in the flash memory [1], [4]. If the interface planes of the anode and the cathode are parallel each other and there is no potential difference in each plane, the traps will be generated uniformly in the plane parallel to the interface.

Fig. 1(a) shows the typical 1-trap and 2-trap path in the oxide. Depending on the construction of 2-trap paths, 2-trap assisted tunneling (two-TAT) current can be larger or smaller than the 1-trap assisted tunneling (single-TAT) current. If we suppose that the current through the path is determined by the longest trap-trap or trap-interface distance [2], 2-trap path can be defined as the path whose trap-trap distance is shorter than the longest trap-interface distance of each 1-trap path so that the current flowing through two traps sequentially is higher than the sum of currents flowing through each trap.

As mentioned above, oxide traps can be assumed to be uniformly distributed in the transverse directions (x-y plane in Fig. 1(a) and (b), where the electric field is applied to z-direction) to the electric field. Let $g_1(z_1)$ be the group of the 1-trap paths whose z-positions are z_1 regardless of their coordinates (x_1, y_1). The paths belonging to $g_1(z_1)$ show the same single-TAT current $I_1(z_1)$. Since the traps are uniformly distributed in the x-y plane, the normalized probability $p_1(z_1)$ of group $g_1(z_1)$ can be expressed as

$$p_1(z_1) = \frac{p(z_1)}{\sum_{z_1} p(z_1)}. \tag{9}$$

From the current $I_1(z_1)$ of each group and the normalized probability $p_1(z_1)$, the PDD of the single-TAT current $f_1(I|1)$ can be obtained.

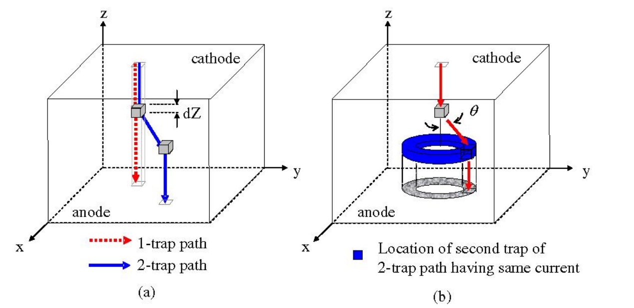

Fig. 1. (a) Configuration of 1-trap path and 2-trap path. (b) Configuration of 2-trap paths showing the same current.

Fig. 1(b) represents the typical group of 2-trap paths showing the same two-TAT current. Let $g_2(z_1, d_{12}, \theta)$ be the group of 2-trap paths in which the z-location of one trap is z_1, the distance between traps is d_{12}, and the angle of the line connecting two traps to the z-axis is θ. The normalized probability $p_2(z_1, d_{12}, \theta)$ of group $g_2(z_1, d_{12}, \theta)$ can be expressed as

$$p_2(z_1, d_{12}, \theta) = \frac{2\pi d_{12}\sin(\theta)p(z_1)p(z_2)}{\sum_{z_1}\sum_{z_2}\sum_{\theta} 2\pi d_{12}\sin(\theta)p(z_1)p(z_2)} \tag{10}$$

where $d_{12} = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2}$.

Similar to $f_1(I|1)$, the PDD of the two-TAT current $f_2(I|1)$ can be obtained from the current $I_2(z_1, d_{12}, \theta)$ and the normalized probability $p_2(z_1, d_{12}, \theta)$ of each group.

Meanwhile, the average number λ_1 of 1-trap paths and the average number λ_2 of 2-trap paths can be obtained as

$$\lambda_1 = \sum_{z_1} p(z_1)D_t V_0 \tag{11}$$

$$\lambda_2 = \sum_{z_1}\sum_{z_2}\sum_{\theta} 2\pi d_{12}\sin(\theta)p(z_1)p(z_2)(D_t V_0)^2 \tag{12}$$

where D_t is the trap volume density and V_0 is the volume of the oxide.

IV. Simulation Results and Discussion

The area and the thickness of the tunnel oxide are $0.06\mu m^2$ and 6.5nm, respectively. The doing densities of the substrate and the gate are 10^{17}cm^{-3} and 10^{20}cm^{-3}, respectively. The gate voltage (V_g) is fixed to 4.0V. Traps are of donor type and their energies are 3.65eV below the edge of conduction band of oxide.

Using the TAT models [1], [9] in the literature, where the capture cross-section σ_n is 10^{-13}cm^2 and the detrapping time τ_e is 10^{-13} sec [1], single-TAT currents and two-TAT currents are calculated. The potentials at the interfaces are obtained from the Poisson-Schrödinger Solver of in-house device simulator NANOCAD [10], and the tunneling probability is calculated using WKB approximation.

To investigate the effect of spatial distribution of traps on the SILC distribution of the cell, traps are assumed to be distributed exponentially as

$$p(z_t) = \frac{\exp(-|t_{ox}/2 - z_t|/\lambda_t)}{2\lambda_t(1-\exp(-t_{ox}/2\lambda_t))} \tag{13}$$

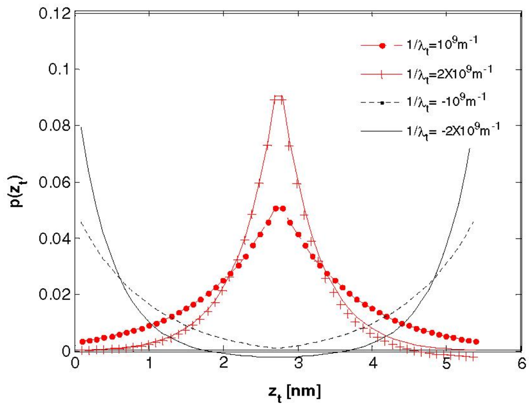

Fig. 2. The spatial distribution of traps.

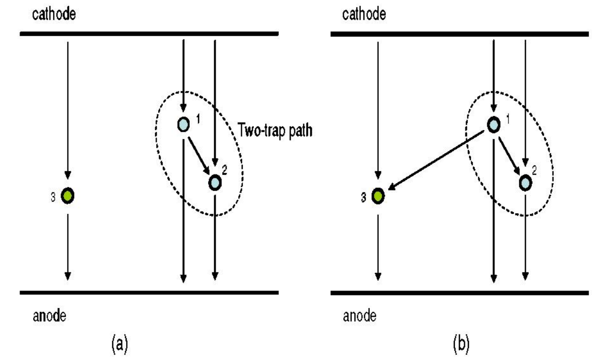

Fig. 4. Current flow through the three adjacent traps (a) in the statistical model and (b) in the MC simulation.

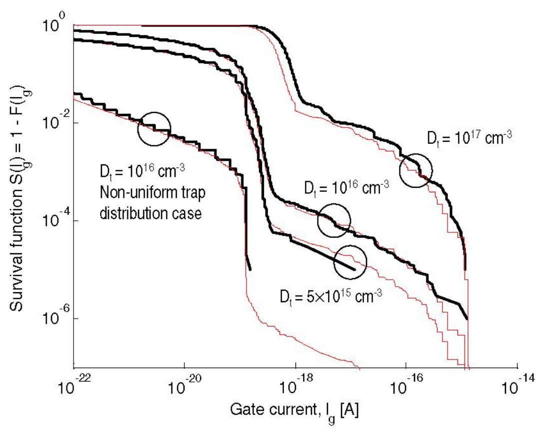

Fig. 3. Survival functions of cell currents calculated by the proposed model (thin line) and by the Monte-Carlo method (bold line).

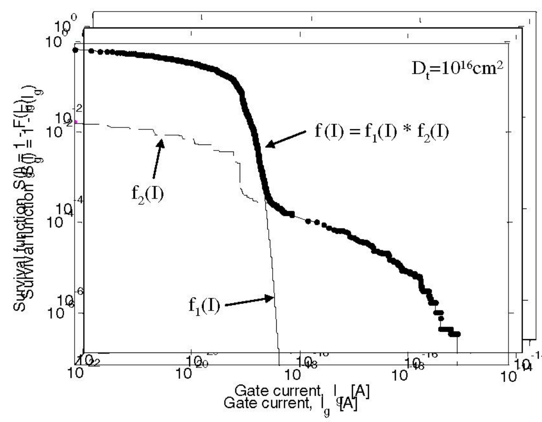

Fig. 5. Survival function of cell current for various trap distribution in the oxide.

where λ_t is the characteristic length representing the exponential variation near the center of the oxide. If $\lambda_t > 0$, the density of traps is maximum at the center of the oxide and decreases exponentially with the distance from the center. In contrast, if $\lambda_t < 0$, the density of traps is maximum at the interfaces and decreases exponentially with the distance from the interface as shown in Fig. 2. As $|\lambda_t|$ decreases, the decrease rate of the trap density increases with the distance from the position of the maximum trap density.

Fig. 3 shows the survival functions of the cell currents calculated by the proposed model and by the Monte-Carlo (MC) method (10^6 samplings for the case of uniformly distributed traps whose volume density D_t=10^{16}cm^{-3}, and 10^5 samplings for others). The statistical model reproduces the results of MC simulation accurately regardless of the volume density and the distribution of traps except the case of high volume density of traps (D_t=10^{17}cm^{-3}). Fig. 4 explains why the current distribution of the statistical model is shifted toward the lower current region compared to that of MC simulation when D_t=10^{17}cm^{-3}. In the statistical model, there can be some traps which do not form the multi-trap path with the traps of the adjacent paths because the distance from the traps of the adjacent paths is longer than the longest trap-interface distance of each trap as shown in Fig. 4(a). In the MC simulation, however, all possible current paths are considered as shown in Fig. 4(b). Therefore, the current calculated by the statistical model will be smaller than that of MC simulation, and the current distribution of the cell moves slightly toward the lower current region in the statistical simulation.

Fig. 5 shows the current PDD $f(I)$ of the cell with two components, the current PDD $f_1(I)$ of 1-trap paths and the current PDD $f_2(I)$ of 2-trap paths. Using the proposed model, the contributions of 1-trap paths and that of 2-trap paths can be analyzed separately.

Fig. 6 shows the effect of the characteristic length λ_t on the distribution of the cell current. Compared to the uniform distribution (λ_t=∞), the current PDD $f(I)$ of the cell becomes small as $|\lambda_t|$ decreases if $\lambda_t < 0$ (trap density is maximum at the interface). On the contrary, if $\lambda_t > 0$ (trap density is maximum at the center of oxide), the current PDD $f_1(I)$ of 1-trap paths becomes large as $|\lambda_t|$ decreases, but the current PDD $f_2(I)$ of 2-trap paths increases and then decreases as $|\lambda_t|$ decreases. These results can be easily explained with the worst-case 1-trap path and 2-trap path [4]. The worst-case path is defined as the path whose current is the largest among the currents of the paths. If the tunneling probability

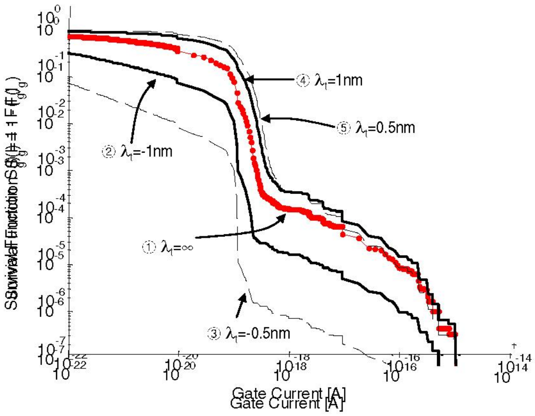

Fig. 6. Survival function of cell current for various trap distribution in the oxide.

is the exponential function of the longest trap-trap and trap-interface distance, the trap position of the worst-case 1-trap path is $(t_{ox}/2)$ and the trap positions of the worst-case 2-trap path are $(t_{ox}/3)$ and $(2t_{ox}/3)$ approximately. As $|\lambda_t|$ decreases, the probability densities $p(t_{ox}/2)$, $p(t_{ox}/3)$ and $p(2t_{ox}/3)$ decreases if $\lambda_t < 0$. Therefore, the current PDD $f(I)$ decreases as $|\lambda_t|$ decreases if $\lambda_t < 0$. In the case of positive λ_t, the probability density $p(t_{ox}/2)$ increases as $|\lambda_t|$ decreases. So, the current PDD $f_1(I)$ of 1-trap paths increases as $|\lambda_t|$ decreases. But, the probability densities $p(t_{ox}/3)$ and $p(2t_{ox}/3)$ increases and then decreases after arriving the peak as $|\lambda_t|$ decreases. Hence, the current PDD $f_2(I)$ of 2-trap paths increases and then decreases as $|\lambda_t|$ decreases.

V. Conclusions

In this paper, we propose a new statistical model to calculate the current PDD of the flash cell from the trap distribution in space. The proposed model reproduces the results of MC simulation accurately if the trap volume density is less than $10^{17}\mathrm{cm}^{-3}$.

Using a new statistical model, we investigate the dependence of the current PDD $f(I)$ of the cell on the trap distribution in the oxide. The PDD of the cell current is found to be very sensitive to the spatial distribution of the traps. In our model, the current PDD $f(I)$ of the cell is composed of the two components, the current PDD $f_1(I)$ of 1-trap paths and the current PDD $f_2(I)$ of 2-trap paths. Therefore, it is possible to analyze the contributions of 1-trap paths and 2-trap paths separately.

Our statistical model is more efficient than the MC method for the calculation of the statistical properties of the rare events such as the retention failure of flash memory whose failure rate is less than 10^{-6}. In the MC simulation, more than 10^7 of samplings have to be performed to guarantee the probability of 10^{-6}. This is very inefficient and time consuming. Hence, our statistical model can be used as a useful tool to analyze the reliability issues.

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