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Anomalous Leakage Current Model for Retention Failure in Flash Memories

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1. Introduction

Oxide reliability is always one of the most crucial issues in flash memories. Although SILC (Stress-Induced Leakage Current) is now widely recognized, a retention lifetime of a megabit-scale memory is determined by a very small number of failure bits showing an anomalously large SILC [1-3]. However no models for the retention lifetime of failure bits have been established yet. In this paper, for the first time, we develop a quantitative model for this anomalous SILC and investigate the properties of retention lifetime of failure bits.

2. Modeling of Anomalous SILC

Since an anomalous SILC is a local conduction phenomenon and its occurrence is a very rare event, it has been observed only at memory cell array consisting of a lot of small area transistors. We have shown by means of a new simulation method that its mechanism is a hopping conduction along a percolated leakage path created by many traps in the oxide [4]. Furthermore we have shown that a rate-limiting process of hopping conduction is an cathode-to-trap tunneling, which causes nearly exponential electric field dependence of the current. For a practical use it is necessary to develop an analytical model which can reproduce the results by numerical simulation. By extracting only the rate-limiting process (Fig. 1) an approximate expression for anomalous SILC is derived;

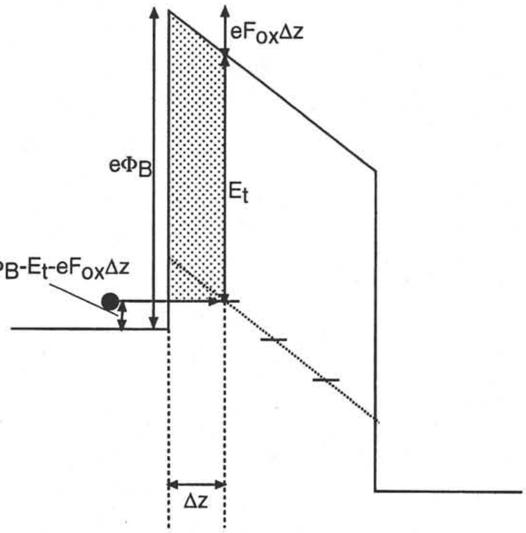

Fig. 1 Energy band diagram and rate-limiting process.

$$I = e \cdot E \cdot D, \tag{1}$$

$$E = \frac{4\pi m (k_B T)^2 \sigma}{h^3} \ln\left[1 + \exp\left\{-\frac{e\Phi_B - E_t - eF_{ox}\Delta z}{k_B T}\right\}\right], \tag{2}$$

$$D = \exp\left[-\frac{8\pi(2m_{ox})^{1/2}}{3heF_{ox}}\left\{(E_t + eF_{ox}\Delta z)^{3/2} - E_t^{3/2}\right\}\right]. \tag{3}$$

Here E, D, σ, E_t, and Δz are emission rate, tunneling probability, capture cross-section, trap level, and cathode-to-trap distance, respectively. Furthermore, by taking account of the injection component from anode and applying a low field approximation we obtain the final expression as follows;

$$I = A \sinh(BF_{ox}), \tag{4}$$

$$A = \frac{8\pi e m (k_B T)^2 \sigma}{h^3} \exp\left\{\frac{E_t - e\Phi_B}{k_B T} - \frac{4\pi(2m_{ox}E_t)^{1/2}\Delta z}{h}\right\}, \tag{5}$$

$$B = \frac{e\Delta z}{k_B T}. \tag{6}$$

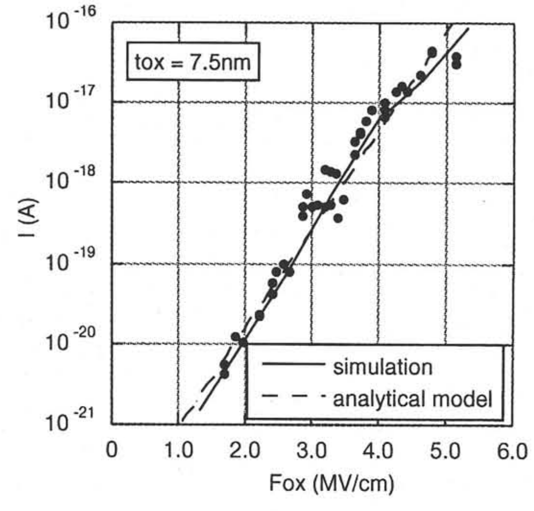

Fig. 2 Comparison between models and experiments for I-Fox characteristics of anomalous SILC.

3. Results and Discussion

First, we fit the models for I-F_{ox} characteristics to the experimental data obtained from biased retention test at various control-gate voltages V_{CG} [1]. Figure 2 shows the comparison between them. The nearly exponential electric field dependence of anomalous SILC is well explained by hopping conduction model. The analytical model can reproduce the simulation results. From this results we obtained $E_t = 2.5$ eV, $\sigma = 1\times10^{-16}$ cm^2, and $\Delta z = 0.75$ nm.

Figure 3 shows the biased retention characteristics at $V_{CG} = -2$V. A remarkable behavior of retention characteristics predicted by our models is a nearly logarithmic time dependence. Furthermore as shown in this figure the Fowler-Nordheim tunneling model, which is often fitted to the anomalous SILC by using a very low barrier height, leads to an overestimation of lifetime at low V_{th} region.

Next we investigate the dominant physical parameters which determine the retention lifetime. Figure 4 shows the electric field dependence of charge-loss time of worst bits at various oxide thicknesses. Here the charge-loss time is defined as a time necessary to lose a fixed number of charges from a floating gate and therefore it's propotional to retention lifetime. As you can clearly see, the charge-loss time is sensitive to the tunnel oxide thickness and the electric field in the oxide and electric field dependence is well explained by our analytical model (solid lines). By fitting the model to the data the oxide thickness dependence of lifetime is empirically included in the trap energy level E_t or capture cross-section of trap σ.

Figure 5 shows the oxide thickness dependence of the trap capture cross-section given by this fitting procedure. Although the physical meaning of thickness dependence of trap parameters has not been clear yet, it is expected to be able to enhance the lifetime by reducing the trap energy level or capture cross-section.

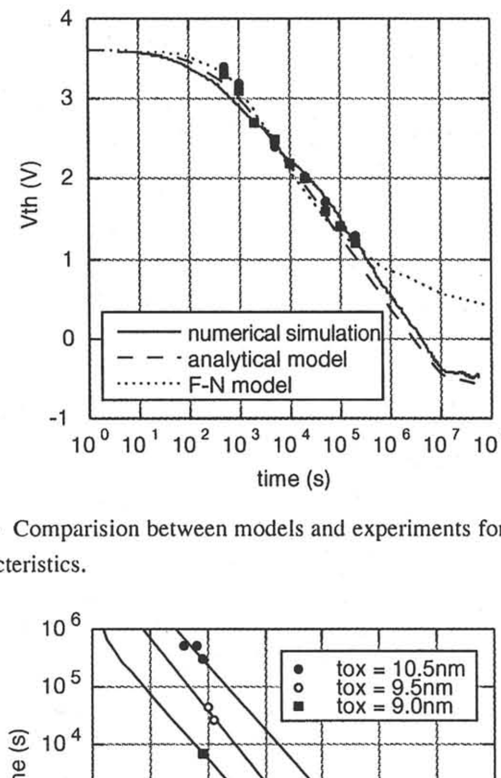

Fig. 3 Comparision between models and experiments for retention characteristics.

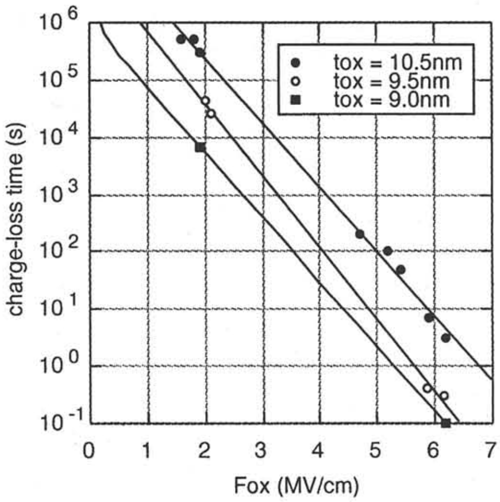

Fig. 4 Comparision between models and experiments for oxide field dependence of charge-loss time.

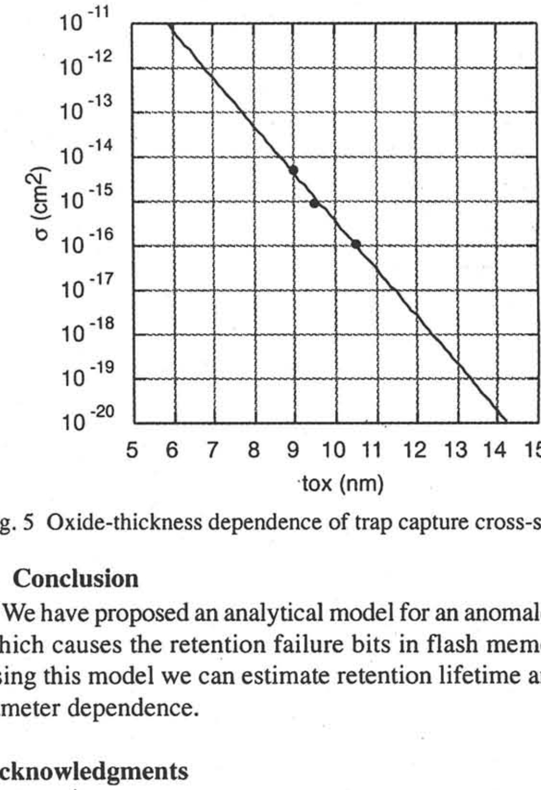

Fig. 5 Oxide-thickness dependence of trap capture cross-section.

4. Conclusion

We have proposed an analytical model for an anomalous SILC which causes the retention failure bits in flash memories. By using this model we can estimate retention lifetime and its parameter dependence.

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