Edge Profile Effect of Tunnel Oxide on Erase Threshold-Voltage Distributions in Flash Memory Cells

Bomsu Kim, Wook-Hyun Kwon, *Member, IEEE*, Chang-Ki Baek, Younghwan Son, Chan-Kwang Park, *Member, IEEE*, Kinam Kim, *Fellow, IEEE*, and Dae M. Kim

Abstract—The erase threshold-voltage (V_T) distribution in Flash electrically erasable programmable read-only memory cells was investigated versus the tunnel oxide edge profiles in self-aligned shallow trench isolation (SA-STI) and self-aligned poly (SAP) cells. The capacitive coupling with offset voltage correction is transcribed into V_T transient for simulating erase V_T dispersion without numerous full structure device simulations. It is shown that SAP gives rise to smaller V_T dispersion, compared with SA-STI. The V_T dispersion resulting from variations in dielectric thickness and oxide edge profiles is shown to fall far short of observed V_T distribution, calling for examination of additional process and cell parameters.

Index Terms—Capacitive coupling equation with offset voltage, edge profile effect, erase threshold voltage distribution, Flash electrically erasable programmable read-only memory (EEPROM) cell.

I. INTRODUCTION

A CRITICAL concern in Flash electrically erasable programmable read-only memory cells is the tight control of V_T within given specifications, especially in multilevel cells [1]. As the cell size gets smaller and the density becomes larger, the small perturbations in processing and operation of the cell give rise to large V_T distributions. Even in fresh virgin cells, the V_T distribution is generally wide, due to the effects of process variations being amplified upon the shrunken cell geometry. V_T further shifts and broadens due to repeated program/erase cycles and trap assisted tunneling or charge loss during retention [2], [3].

V_T dispersion in small cells is more sensitively affected by local effects such as the discrete dopant fluctuation [4]–[7], random polysilicon grain size [8], etc., Also, because of the high packing density the interference between adjacent cells results in further V_T shifts [9]. Recently, the control of the edge-profile of the tunnel oxide in 90-nm NOR Flash memory cells was shown to improve V_T distribution [10], [11], indicating that the edge geometry also affects V_T .

Manuscript received June 6, 2006; revised August 18, 2006. This work was supported by Samsung Electronics, Inc. under a research grant. The review of this paper was arranged by Editor V. R. Rao.

B. Kim, C.-K. Baek, Y. Son, and D. M. Kim are with the School of Computational Sciences, Korea Institute for Advanced Study (KIAS), Seoul 130-722, Korea.

W.-H. Kwon, C.-K. Park, and K. Kim are with the Advanced Technology Development Team, Semiconductor R&D Center, Samsung Electronics Company, Ltd., Gyeonggi-Do 449-711, Korea.

Color versions of Figs. 3, 4, and 9 are available at <http://ieeexplore.ieee.org>. Digital Object Identifier 10.1109/TED.2006.885101

In downsizing the cell, its width constitutes the critical dimension. The large drain voltage required for the channel hot electron injection in NOR-type cells renders the cell vulnerable to the punchthrough effect, preventing the channel length reduction. In contrast, shrinking the channel width is free of such constraints and has the additional advantage of low programming current. In a narrow channel width, however, the edge effects of tunnel oxide become prominent such as the electric field crowding, affecting gate current and thus V_T .

In Section II, the erase V_T distribution due to the one-dimensional uniform variation of oxide-nitride-oxide (ONO) or tunnel oxide thickness is analytically discussed, giving an insight into the V_T dispersion. The V_T transient equation derived from the capacitive couplings with the offset voltage correction is shown to describe V_T distributions, when the specific process variations are embedded into the general cell parameters. In Section III, a fast simulation of the erase V_T distribution due to the oxide edge effects associated with self-aligned shallow trench isolation (SA-STI) [12] and self-aligned poly (SAP) [13] is performed without resorting to the full structure device simulations, and a few conclusions are drawn in Section IV.

II. BACKGROUND DISCUSSION

A. Capacitive Coupling Equation and V_{offset}

The well-known capacitive coupling equation [14] generally has additional offset voltage terms (V_{offset}), which assumes different values depending on channel accumulation or inversion due to the work function difference between the terminals and channel depletion capacitance [15], [16]

$$V_{\text{FG}} = \alpha_{\text{CG}} V_{\text{CG}} + Q_{\text{FG}}/C_T + V_{\text{offset}}. \quad (1)$$

Here, the drain, source, and bulk terms are deleted since they are always grounded in this paper. The Gauss law applied to the floating-gate terminal yields $V_{\text{offsetI}} = (V_{\text{FB}} + 2\phi_B) \times C_{\text{TNL}}/C_T$ and $V_{\text{offsetA}} = V_{\text{FB}} \times C_{\text{TNL}}/C_T$ in channel inversion and accumulation, respectively. Here, V_{FB} is the flatband voltage between the floating-gate and the bulk, C_{ONO} and C_{TNL} the interpoly and tunnel oxide capacitances (cf. $C_T = C_{\text{ONO}} + C_{\text{TNL}}$), and ϕ_B is the bulk Fermi potential so that $2\phi_B$ represents the surface bending at the onset of strong inversion.

Fig. 1. (a) Band diagram in Flash memory cells with on- and off-target ONO thickness, in erase where a negative bias is applied at the control gate and (b) in reading where the floating-gate voltage is fixed at given V_{TFG} .

B. Erase V_T versus Uniform Dielectric Thickness Variation

As the first step for understanding the erase V_T distribution, consider the effect of uniform variation of ONO thickness (t_{ONO}) from its target value (t_{ONO}^*) across the gate electrode. Fig. 1(a) shows the energy band diagram in erase, drawn in solid and dashed lines for on-target (t_{ONO}^*) and off-target (t_{ONO}) cells, respectively. Here, use has been made of the fact that the tunnel oxide electric field assumes the same value at the end of erase [3], regardless of the value of programmed V_T or ONO thickness. This property is detailed in Appendix. Since the tunnel oxide electric fields are the same for the case of both t_{ONO} and t_{ONO}^* , the difference in the stored charge in the floating-gate is given by

$$\Delta Q_{FG} = (C_{ONO} - C_{ONO}^*) (V_{FGe}^* - V_{CGe}^*) \quad (2)$$

where C_{ONO}^* and C_{ONO} are the ONO capacitances in on- and off-target cells and V_{FGe}^* and V_{CGe}^* are the common floating and control gate voltages [see Fig. 1(a)].

The erase V_T is affected by both $\Delta t_{ONO} (= t_{ONO} - t_{ONO}^*)$ and ΔQ_{FG} . To estimate the change in V_T , first introduce ΔV_{Te1} due to Δt_{ONO} , while putting $\Delta Q_{FG} = 0$. In this case, the electric field in ONO is the same in both cells, as shown in Fig. 1(b) and ΔV_{Te1} is thus given by

$$\Delta V_{Te1} = (\Delta t_{ONO} / t_{ONO}^*) (V_{Te}^* - V_{TFG}^*) \quad (3)$$

where V_{Te}^* is the threshold voltage at the control gate after erase, and V_{TFG}^* is that at floating-gate.

Next, ΔV_{Te2} due to ΔQ_{FG} can be found by using (2) and $C_{ONO} / C_{ONO}^* = t_{ONO}^* / t_{ONO}$

$$\begin{aligned} \Delta V_{Te2} &\equiv -\Delta Q_{FG} / C_{ONO} \\ &= (t_{ONO} / t_{ONO}^* - 1) (V_{FGe}^* - V_{CGe}^*). \end{aligned} \quad (4)$$

The total V_T variation $\Delta V_{Te} = \Delta V_{Te1} + \Delta V_{Te2}$ is thus given by

$$\Delta V_{Te} = (\Delta t_{ONO} / t_{ONO}^*) (V_{Te}^* - V_{TFG}^* + V_{FGe}^* - V_{CGe}^*). \quad (5)$$

Here, V_{TFG}^* and V_{FGe}^* are implicit voltages and can be replaced with the known voltages V_{Te}^* , V_{CGe}^* using (1) for both channel inversion and accumulation, obtaining

$$\Delta V_{Te} \approx \frac{\Delta t_{ONO}}{t_{ONO}^*} (1 - \alpha_{CG}^*) (V_{Te}^* - V_{CGe}^*). \quad (6)$$

One can also analyze the erase V_T change due to the uniform variation of tunnel oxide thickness Δt_{OX} in a similar manner, obtaining an expression symmetric with respect to (6)

$$\Delta V_{Te} \approx \frac{\Delta t_{OX}}{t_{OX}^*} \alpha_{CG}^* (V_{Te}^* - V_{CGe}^*). \quad (7)$$

In (6) and (7), ΔV_{Te} is characterized in terms of $\Delta t_{ONO} / t_{ONO}^*$, $\Delta t_{OX} / t_{OX}^*$ and operating voltages. Clearly, the V_T variation can be made small by reducing V_{Te}^* and V_{CGe}^* but reducing V_{Te}^* is limited by the overerase margin, while small V_{CGe}^* necessitates long erase time. Also, since the variations, $\Delta t_{ONO} / t_{ONO}^*$ and $\Delta t_{OX} / t_{OX}^*$ are basically unknown quantities, it appears reasonable to keep α_{CG}^* at about 0.5. In this case, for typical values of $V_{Te}^* = 3$ V, $V_{CGe}^* = -17$ V, $\Delta t_{ONO} / t_{ONO}^*$ or $\Delta t_{OX} / t_{OX}^*$ of $\pm 5\%$ is shown to give the erase V_T shift of $\Delta V_{Te} \sim \pm 0.5$ V centered at 3 V.

Next, the erase V_T change due to the nonuniform local effect such as the edge profile of the tunnel oxide is examined in the following section.

C. Transient V_{FG} and V_T During Erase

The time-dependent equations of V_{FG} and V_T during the erase are derived from the basic capacitive coupling. These equations can quantify the transient V_{FG} and V_T versus the process variations. The analytical solution of V_{FG} and V_T transients were derived in terms of specific cell parameters in [15]. However, the transient equations presented here are specified by more general set of parameters, so that various process variations, e.g., the local edge effects of tunnel oxide, can be easily embedded into each parameter.

In the present approach V_{FG} , V_T transients are analyzed by switching back and forth between erase and read modes. During the erase, in which the control gate is constantly biased at V_{CGe} while other terminals are grounded, the excess charge Q_{FG} in the floating-gate is tunneled out as gate current, I_G , i.e., $dQ_{FG} / dt = I_G$. Here, I_G depends on changing V_{FG} , viz., $I_G = I_G(V_{FG})$. Since the cell terminals are all kept constant during the erase, differentiating (1) in accumulation with time yields [17]

$$\frac{dV_{FG}}{dt} = \frac{1}{C_T} \cdot \frac{dQ_{FG}}{dt} = \frac{I_G(V_{FG})}{C_T}. \quad (8)$$

The initial value of $V_{FG}(t)$ is obtained from (1) in both accumulation and inversion, operative, respectively, at the beginning of erase and read at the end of programming. In this case, Q_{FG} is the same and by subtracting (1) in inversion from (1) in accumulation there results with $\alpha_{CG} = C_{ONO} / C_T$

$$V_{FG0} = V_{TFG} + \frac{C_{ONO}}{C_T} (V_{CGe} - V_{T0}) + \Delta V_{offset}. \quad (9)$$

Fig. 2. (a) Erase V_T versus nominal process parameter variation with respect to the target values: interpoly and tunnel oxide capacitances, C_{ONO} , C_{TNL} ; (b) tunneling gate current, I_G ; (c) threshold voltage of floating-gate, V_{TFG} .

Here, V_{FG0} is the initial V_{FG} in erase and V_{T0} the user-definable initial V_T at the control gate in erase, or equivalently final V_T at the end of programming and $\Delta V_{offset} = V_{offsetA} - V_{offsetI}$.

In reading mode, V_{TFG} is, by definition, fixed at a value determined solely by the onset of strong inversion, while V_T at the control gate changes. Thus, by differentiating (1) in inversion with respect to time one finds

$$0 = \alpha_{CG} \frac{dV_T}{dt} + \frac{1}{C_T} \cdot \frac{dQ_{FG}}{dt} \quad (10)$$

(10) and (8) provide a linear relationship between ΔV_T and ΔV_{FG}

$$\Delta V_T = -\frac{1}{\alpha_{CG}} \Delta V_{FG}. \quad (11)$$

Thus, the change in time of V_T from V_{T0} is given in terms of that of V_{FG} from V_{FG0} . Now, V_{FG0} and V_{T0} are related by (9) and one can write from (9) and (11)

$$V_T(t) = V_{CGe} - \frac{C_T}{C_{ONO}} [V_{FG}(t) - V_{TFG} - \Delta V_{offset}]. \quad (12)$$

The set of equations (8), (9), and (12) makes it possible to simulate the transient behavior of V_{FG} and V_T in terms of the pertinent cell parameters (C_{ONO} , C_{TNL} , I_G , and V_{TFG}). Any random process variation is to be represented in corresponding variation of one of these parameters. For example, the discrete dopant fluctuation causes V_{TFG} variation, while the polysilicon grain size affects I_G . Also, the nonuniform edge profile alters both I_G and C_{TNL} .

The contribution of these parameters to the erase V_T distribution, ΔV_{Te} can be calculated by varying each parameter, while keeping others fixed to the target values and by solving (8), (9), and (12). Fig. 2 shows the result obtained versus the cell parameter variations for two different erase voltages, $V_{CGe} = -15$ V and -17 V. In the calculation, V_{Te} is set to 3 V, and the erase time was set to 90 ms or 1.3 ms for $V_{CGe} = -15$ V or -17 V, respectively. Also, I_G^* was measured from an array pattern and V_{TFG}^* was found from unit reference cell where floating and control gates are shorted. Also, C_{ONO}^* and C_{TNL}^* were obtained by simulating TEM cross section [10]. These

target parameters are slightly altered to fit the observed erase V_T versus time, resulting in $V_{TFG}^* = 2$ V, $C_{ONO}^* = 5.13 \times 10^{-16}$ F/ μm , and $C_{TNL}^* = 4.37 \times 10^{-16}$ F/ μm (normalized in length).

As clear from Fig. 2(a), the relative variations, $\Delta C_{ONO}/C_{ONO}^*$, $\Delta C_{TNL}/C_{TNL}^*$ by 10% is shown to give about $\Delta V_T \approx 1$ V with larger V_{CGe} inducing slightly greater change. These results are consistent with the predictions of (6) or (7). Also, I_G variation by an order of magnitude centered at I_G^* results in $\Delta V_T \approx 1$ V [Fig. 2(b)]. Finally, ΔV_{TFG} by say 0.5 V gives rise to ΔV_{Te} by about 1 V, corresponding to about $\Delta V_{TFG}/\alpha_{CG}$ [Fig. 2(c)]. It is interesting to note that Fig. 2 provides a simple means by which to single out the dominant cause of ΔV_{Te} by measuring the V_T distribution using different erase voltage at the control gate V_{CGe} . For example, if V_T distribution has an appreciable dependence on V_{CGe} , the dominant cause is I_G variation, while a weak dependence points to the dominance of V_{TFG} variation.

The erase V_T variations in Fig. 2 are approximately linear with respect to the input parameters and the total V_T distribution can therefore be estimated by $\sigma_{total}^2 = \sigma_{C_{ONO}}^2 + \sigma_{C_{TNL}}^2 + \sigma_{I_G}^2 + \sigma_{V_{TFG}}^2$, where σ is the width of V_T distribution. The total distribution can also be calculated directly from (8), (9), and (12) by randomly varying the parameters simultaneously. Now, that ΔV_{Te} has been specified via the random variations of cell parameters, the next task is to discuss the origins of such variation. In Section III, the edge profile of the gate oxide is discussed as an example.

III. ERASE V_T DISTRIBUTION VERSUS OXIDE EDGE PROFILE

To simulate the erase V_T distribution versus the tunnel oxide edge profile, one could perform the transient device simulation incorporating a large number of randomly generated profiles in conjunction with control (CG) and floating (FG) gates, ONO and tunnel oxide (OX), and the substrate (SUB). In this paper, this direct simulation is bypassed in favor of two time-saving measures. First, the device simulations are confined to the FG–OX–SUB structure and the gate current (I_G) and tunnel oxide capacitance (C_{TNL}) associated therein. Then, the transient simulation of the cell is performed for each different edge profile by using (8), (9), and (12), with I_G and C_{TNL} explicitly inserted. By bypassing the full structure simulation, more mesh nodes can be assigned to the edge region for accurate simulation of electric field and I_G , giving thereby the benefits to the three-dimensional simulation. Second, a meaningful simulation of V_T distribution requires sample numbers stretching to several orders, and prohibitively large simulation time. This difficulty is circumvented by simulating in advance specific numbers of sample and incorporating other samples via interpolation within the sample matrix, to be detailed later.

Fig. 3 depicts the cross-sectional edge structure along the width in SA-STI [Fig. 3(a)] and SAP [Fig. 3(b)] processed cells. The parameters of the target cells are t_{OX} at the center of 85 Å, and cell width (W) of 90 nm and the substrate doping of $N_A = 2 \times 10^{18}$ cm $^{-3}$. I_G was simulated versus V_{FG} and the tunnel oxide capacitance was extracted for use in (8), (9),

Fig. 3. Cross-sectional views of the floating-gate-tunnel oxide-substrate structures in (a) SA-STI and (b) SAP cells.

and (12). A particular attention was paid to the mesh formation near the edge in SA-STI, since the tunneling current depends sensitively on the mesh size around the edge boundaries. This apparent errorlike mesh dependence is due to the angle (θ) at the edge remaining unchanged regardless of the mesh size [see the inset of Fig. 3(a)]. This implies a different radius of curvature at the edge for different mesh size. For the case of SAP, there was no such mesh-dependent anomaly, and the material boundaries are sufficiently smooth to render both the mesh lines on the boundary and the angle between them conform to the boundaries.

In this paper, the boundary conforming to the small radius of curvature was not used, since it is difficult to deal with in Medici [18] mesh generator. Rather, an ideal edge profile shown in the inset of Fig. 3(a) was used, with the same topology of mesh triangulations for all samples to avoid the mesh-dependent I_G fluctuation. The mesh size was chosen to be 3 Å in the oxide near the edge for accommodating the abrupt change of electric field, and to be 2 nm on the edge boundaries for relieving the extremely high electric field and high tunneling current by way of averaging the electric field in the mesh element.

Fig. 4 shows the simulation flow of the erase V_T distribution. Here, the boundary files for specified variation were generated by selecting tunnel oxide thickness (ΔT_{OX}), edge thickness (ΔE), and cell width (ΔW) as random process variations [Fig. 4(a)]. Each variation was ranged in common from -10 to 10 Å, and seven samples were selected at regular intervals, so that the matrix of $7 \times 7 \times 7$ samples was selected for simulation [Fig. 4(b)]. Both I_G and C_{TNL} were simulated in these samples with erase V_T s calculated using (8), (9), and (12) [Fig. 4(c)]. V_{TFG} change was assumed to be caused only by ΔT_{OX} . For erase V_T distribution, 512 K samples were randomly selected following the Gaussian distribution from the sample matrix [Fig. 4(d)] and the erase V_T s were computed by interpolating V_T versus ΔT_{OX} , ΔE , and ΔW in Fig. 4(c). Naturally, V_T variation should be smooth in the sample matrix, so that the interpolation gives reliable result using an adequate number of samples chosen within the variation range. This requirement was met in the sample matrix chosen.

Fig. 5 shows I_G , C_{TNL} , and V_T versus ΔT_{OX} , ΔE , or ΔW for both SA-STI and SAP. These results were obtained by varying only one parameter while keeping others fixed. Clearly, I_G is shown to vary significantly in SA-STI cells with ΔT_{OX} , ΔE , and ΔW , while SAP processed cells exhibit a large I_G variation only with ΔT_{OX} [Fig. 5(a)]. The behavior of C_{TNL} is roughly same in both cells, undergoing a large variation with ΔT_{OX} [Fig. 5(b)]. The change of V_{TFG} due to ΔT_{OX} is same for both process types. With I_G , C_{TNL} , and V_{TFG} thus obtained, the erase V_T was calculated by using (8), (9), and (12). The common parameters used for calculation are: $V_{TFG}^* = 2$ V, $V_{CGe} = -17$ V, $\phi_B = 0.48$ V, and $V_{T0} = 9$ V. Also, C_{ONO} was chosen such that $\alpha_{CG} = 0.54$ at the target sample and the erase V_T at the target sample was chosen to be 3 V by adjusting the erase time in both cells. As clear from Fig. 5(c) the dominant parameters affecting V_T are the variation of the edge profile (ΔE) and the tunneling oxide thickness (ΔT_{OX}) in SA-STI and SAP samples, respectively.

Fig. 6 shows the simulated V_T distributions of SA-STI and SAP cells, obtained by sampling 512 K cells. The 3σ random variations of ΔT_{OX} , ΔE , and ΔW were fixed at 1, 1, and 3 Å, respectively. As clear from Fig. 6, V_T in SA-STI cells is shown sensitively affected by edge profile parameters, and a large V_T distribution ensues due to the 3σ random variations of ΔE and ΔW . On the other hand, the V_T distribution of SAP cells is mainly determined by ΔT_{OX} , and is nearly independent of the edge profile variations. Since the controllability of the edge region is in general difficult, SA-STI processed cells are expected to have a broader V_T distribution, compared with SAP cells (see black and white square symbols in Fig. 6).

Fig. 7 shows the V_T distributions measured from SA-STI and SAP samples. Clearly SAP cells have a width narrower by about 0.2–0.3 V, compared to the former. However, the measured distributions are still much broader than those resulting from the edge profile effects discussed in Fig. 6. A quantitative comparison between the simulation and measured data was made as follows. First, a common “background distribution” was introduced for both cells, accounting for all possible process variations excluding the ones (ΔT_{OX} , ΔE , and ΔW) in Fig. 4(a). Since these two cells are processed identically other than the edge profiling in the length direction it is reasonable to take the background distribution to be the same in both cells and analyze the edge effect separately as in Fig. 6. Combined to this background was the additional distribution arising from the edge effects simulated in Fig. 6 by using $3\sigma_{TOX} = 1$ Å, $3\sigma_E = 3$ Å, and $3\sigma_W = 3$ Å.

It is important to point out that a fit to the data necessitates the introduction of a large background distribution, which in turn suggests additional parameters inherently operative and independent of the edge profile control contributing to the V_T dispersion. This broad background distribution can be understood in part in terms of the random process variations of ONO, ΔV_{TFG} by discrete dopant fluctuation being amplified by $1/\alpha_{CG}$ at the control gate with α_{CG} itself varying from cell to cell, the cell-to-cell interference, random polygrain size, surface roughness, the edge effects along the cell width direction, etc.

Fig. 8 shows the standard deviation, σV_T of V_T distributions as a function of the cell width, W . For $3\sigma_{TOX} = 1$ Å,

Fig. 4. Simulation flow of erase V_T distribution. Fig. 5. Relative variations of (a) gate current and (b) tunnel oxide capacitance with respect to the target value, and the erase V_T variation corresponding to (a) and (b) versus ΔT_{OX} , ΔE , and ΔW in both SA-STI and SAP cells.

$3\sigma_E = 3 \text{ \AA}$, and $3\sigma_W = 3 \text{ \AA}$, σV_T of SA-STI cells tends to increase slightly with decreasing W . This is because the V_T variation in this case is dominated by the edge profile effect while the reduction of the main tunneling region with decreasing W plays an insignificant role. However, σV_T of SAP cells increases faster, as W decreases and the main tunneling region is reduced therein. A highlight of Fig. 8 consists of the fact that within W range considered, σV_T of SAP cells is smaller by a

Fig. 6. Simulated erase V_T distributions of SA-STI and SAP cells for different combinations of ΔT_{OX} , ΔE , and ΔW , showing the edge profile sensitivity of SA-STI cells.

factor 2, compared with SA-STI cells. This indicates that the SAP is suitable for cell scaling even if the edge profiling is to be controlled within 2- $\text{\AA}$ accuracy. As an additional note, σV_T of SAP cells is consistent with the prediction given by (7) as the edge effects are reduced and the cell width becomes longer.

Fig. 7. Comparison of measured and simulated V_T distributions of SA-STI and SAP cells.

Fig. 8. Standard deviation of erase V_T distributions of SA-STI and SAP cells versus the width.

IV. CONCLUSION

The erase V_T distribution in Flash memory cells was investigated as a function of the random process variations. Instead of the full-structure device simulations, the capacitive coupling equations with offset voltage correction were used to simulate the time dependent V_T for different values of cell parameters (C_{ONO} , C_{TNL} , I_G , and V_{TFG}). Specific random process variation can be embedded into the cell parameters for analyzing its effect on erase V_T distribution.

The method was applied to comparing two current process technologies, viz., SA-STI and SAP for the tunnel oxide edge effects on the erase V_T distributions. The angled edge geometry in SA-STI cells with high tunneling current by electric field crowding near the edge region, combined with the relatively difficult control of edge profile, leads to wider V_T dispersion than SAP cells. On the other hand, the SAP cells, relatively free of the edge effect are also shown to be more suitable for cell scaling. A good fit to the V_T distribution measured from SA-STI and SAP cells was shown to require a broad background V_T distribution. This means that the tunnel oxide edge effects

Fig. 9. (a) Family of gate currents generated to mimic I_G from an ensemble of cells and the corresponding final floating-gate voltage found numerically at the end of erase (dots). (b) Corresponding plot calculated from (A.3).

constitute a mere fraction of the total observed distribution. It is therefore important to identify and further analyze these additional effects for optimizing the process parameters of small cell geometries.

APPENDIX

The FN tunneling gate current can be approximated via the first order Taylor expansion of V_{FG} near the final erase V_{FG} , i.e., V_{FGe} as

$$I_G = I_{G0} \cdot e^{K \cdot V_{FG}} \quad (A.1)$$

where I_{G0} and K are constants depending on V_{FGe} [3].

Under FN erase V_{FG} quickly decreases from its initial value V_{FG0} and approaches the final V_{FGe} asymptotically, taking up most of the erase time t_e . Insert (A.1) into (8) and solve the differential equation, obtaining

$$e^{-K \cdot V_{FGe}} - e^{-K \cdot V_{FG0}} = \frac{K \cdot I_{G0}}{C_T} t_e. \quad (A.2)$$

Since $|V_{FG0}|$ is much larger than $|V_{FGe}|$ the second term of (A.2) is neglectable and one can write (A.2) as $K I_{G0} t_e / C_T = 1$ with $I_{Ge} = I_{G0} \exp K V_{FGe}$, regardless of any initial V_{FG0} . Since $K I_{Ge}$ is the slope of (A.1) at V_{FGe} , one can generalize (A.1) as

$$I'_G(V_{FGe}) \cdot \frac{1}{C_T} \cdot t_e = 1 \quad (A.3)$$

where $I'_G = dI_G/dV_{FG}$. (A.3) constitutes the condition determining the erase V_{FG} implicitly for given t_e .

Fig. 9(a) shows a family of FN tunneling currents. In each I_G curve, (8) was solved numerically with given erase time of $t_e = 10$ ms, obtaining V_{FGe} . In generating a family of I_G curves, C_T was randomly varied around its target value to simulate the I_G s at different memory cells. The resulting V_{FGe} is presented as a dot on each I_G curve. Shown in Fig. 9(b) is corresponding $(dI_G/dV_{FG})/C_T$ together with V_{FGe} versus V_{FG} . As clearly exhibited in Fig. 9(b), the trace of V_{FGe} s accurately determines $1/t_e$ for all curves considered,

conclusively proving the validity of the termination condition (A.3) and the related assumptions. Also, in Fig. 9(a), the trace of V_{FGe} s well approximates a straight line indicating constant I_G as an approximated condition. Constant I_G implies a constant electric field in the tunnel oxide, whose condition is already used in Section II-B and [3]. Finally, it is noted that ΔV_{Te} due to varying I_G can also be estimated via $\Delta V_{\text{FG}}/\alpha_{\text{CG}}$ with ΔV_{FG} found in a manner as in Fig. 9(a).

REFERENCES

- [1] B. Eitan, R. Kazerounian, A. Roy, G. Crisenza, P. Cappelletti, and A. Modelli, "Multilevel Flash cells and their trade-offs," in *IEDM Tech. Dig.*, 1996, pp. 169–172.
- [2] J.-D. Lee, J.-H. Choi, D. Park, and K. Kim, "Effects of interface trap generation and annihilation on the data retention characteristics of Flash memory cells," *IEEE Trans. Device Mater. Rel.*, vol. 4, no. 1, pp. 110–117, Mar. 2004.
- [3] N. Mielke, H. Belgal, I. Kalastirsky, P. Kalavade, A. Kurtz, Q. Meng, N. Righos, and J. Wu, "Flash EEPROM threshold instabilities due to charge trapping during program/erase cycling," *IEEE Trans. Device Mater. Rel.*, vol. 4, no. 3, pp. 335–344, Sep. 2004.
- [4] A. Asenov, "Random dopant induced threshold voltage lowering and fluctuations in sub-0.1 μm MOSFETs: A 3-D 'atomistic' simulation study," *IEEE Trans. Electron Devices*, vol. 45, no. 12, pp. 2505–2513, Dec. 1998.
- [5] A. Asenov, A. R. Brown, J. H. Davies, S. Kaya, and G. Slavcheva, "Simulation of intrinsic parameter fluctuations in decanometer and nanometer-scale MOSFETs," *IEEE Trans. Electron Devices*, vol. 50, no. 9, pp. 1837–1852, Sep. 2003.
- [6] N. Sano, K. Matsuzawa, M. Mukai, and N. Nakayama, "Role of long-range and short-range Coulomb potentials in threshold characteristics under discrete dopants in sub-0.1 μm Si-MOSFETs," in *IEDM Tech. Dig.*, 2000, pp. 275–278.
- [7] T. Ezaki, T. Ikezawa, and M. Hane, "Investigation of realistic dopant fluctuation induced device characteristics variation for sub-100 nm CMOS by using atomistic 3D process/device simulator," in *IEDM Tech. Dig.*, 2002, pp. 311–314.
- [8] S. Muramatsu, T. Kubota, N. Nishio, H. Shirai, M. Matsuo, N. Kodama, M. Horikawa, S. Saito, K. Arai, and T. Okazawa, "The solution of over-erase problem controlling poly-Si grain size-modified scaling principles for Flash memory," in *IEDM Tech. Dig.*, 1994, pp. 847–850.
- [9] W. H. Lee, "The effect of dimensional scaling on the erase characteristics of NOR Flash memory," *IEEE Electron Device Lett.*, vol. 24, no. 4, pp. 245–247, Apr. 2003.
- [10] W. H. Kwon, J. I. Han, B. Kim, C.-K. Baek, S.-P. Sim, W. H. Lee, J. H. Han, C. Jung, H. K. Lee, Y. K. Jang, J. H. Park, D. M. Kim, C.-K. Park, and K. Kim, "Highly reliable 256 Mb NOR Flash MLC with self-aligned process and controlled edge profile," in *Proc. Int. Conf. SSDM*, Kobe, Japan, 2005, pp. 448–449.
- [11] S.-P. Sim, W. H. Kwon, C. H. Lee, J. I. Han, W. H. Lee, C. Jung, H. K. Lee, Y. K. Jang, S. W. Park, J. H. Park, C.-K. Park, K. T. Kim, and K. Kim, "A 90 nm generation NOR Flash multilevel cell (MLC) with 0.44/spl mu/m/sup 2/bit cell size," in *Proc. IEEE VLSI-TSA Int. Symp. VLSI Tech.*, 2005, pp. 35–36.
- [12] Y. Song, S. Lee, T. Kim, J. Han, H. Lee, S. Kim, J. Park, S. Park, J. Choi, J. Kim, D. Lee, M. Cho, K. Park, and K. Kim, "Highly manufacturable 90 nm NOR Flash technology with 0.081 /spl mu/m/sup 2/ cell size," in *VLSI Symp. Tech. Dig.*, 2003, pp. 91–92.
- [13] S. N. Keeney, "A 130 nm generation high density EtoX Flash memory technology," in *IEDM Tech. Dig.*, 2001, pp. 41–44.
- [14] P. Cappelletti, C. Golla, P. Olivo, and E. Zanoni, *Flash Memories*. Boston, MA: Kluwer, 1999, pp. 4–6.
- [15] A. Kolodny, S. T. K. Nieh, B. Eitan, and J. Shappir, "Analysis and modeling of floating-gate EEPROM cells," *IEEE Trans. Electron Devices*, vol. ED-33, no. 6, pp. 835–844, Jun. 1986.
- [16] C.-K. Baek, B. Kim, Y. Son, W. Kwon, C.-K. Park, Y. J. Park, H. S. Min, and D. M. Kim, "Reliable extraction of cycling induced interface states implementing realistic P/E stresses in reference cell: Comparison with Flash memory cell," *IEEE Electron Device Lett.*, vol. 27, no. 3, pp. 169–171, Mar. 2006.
- [17] D. Esseni, A. D. Strada, P. Cappelletti, and B. Ricco, "A new and flexible scheme for hot-electron programming of nonvolatile memory cells," *IEEE Trans. Electron Devices*, vol. 46, no. 1, pp. 125–133, Jan. 1999.
- [18] *Medici User Guide*, Synopsys Inc., Mountain View, CA, Jun. 2003.

Bomsoo Kim was born in Seoul, Korea, in 1977. He received the B.S. and Ph.D. degrees in electronic and electrical engineering, both from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2000 and 2005, respectively.

Currently, he is a Research Fellow of the School of Computational Sciences at Korea Institute for Advanced Study (KIAS). His research interests include the semiconductor device modeling and simulation, especially on the reliability of Flash memory cells.

Wook-Hyun Kwon (S'95–M'97) was born in Seoul, Korea, in 1972. He received the B.S. degree in physics from Jung-ang University, Seoul, Korea, in 1995 and the M.S. degree in electrical engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1997.

From 1997 to 2002, he was with Hyundai Electronics Industries Company, Ltd., Icheon, Korea, where he developed high-density Flash memories. In 2003, he joined the Samsung Electronics Company, Ltd., Giheung, Korea, where he has been engaged in the research and development of high-density NOR Flash memories. His research interests are device modeling, process integration, design, and reliability for high-density nonvolatile memories.

Chang-Ki Baek was born in Seoul, Korea, in 1973. He received the M.S. degree in electronic and electrical engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2002. He is currently working toward the Ph.D. degree in electrical engineering and computer science at Seoul National University.

His current research interests include the device analysis and modeling of Flash memory cells.

Younghwan Son was born in Daejeon, Korea, in 1981. He received the B.S. degree in electrical engineering from Chungnam National University, Daejeon, in 2004, where he is currently working toward the M.S. degree.

Since 2005, he has been with the School of Computational Sciences, Korea Institute for Advanced Study (KIAS), Seoul, Korea. His research interests include the device analysis and modeling of Flash memory cells, and reliability issues of nano-CMOS devices.

Chan-Kwang Park (S'90–M'92) was born in Incheon, Korea, in 1961. He received the B.S. degree in electronic engineering from Sogang University, Seoul, Korea, in 1984 and the M.S. and Ph.D. degrees in electrical engineering from Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 1987 and 1992, respectively.

From 1992 to 2002, he was with Hyundai Electronics Industries Company, Ltd., Icheon, where he developed high-density dynamic random access memories (DRAMs). In 2003, he joined the Samsung Electronics Company, Ltd., Giheung, Korea, where he engaged in the research and development of high-density NOR Flash memories. His research interests are device modeling, process integration, design, and reliability for high-density nonvolatile memories.

Kinam Kim (S'90–M'97–SM'01–F'03) received the B.Sc. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1981, the M.S. degree in electrical engineering from Korea Advanced Institute of Science and Technology, Seoul, in 1983, and the Ph.D. degree in electrical engineering from the University of California at Los Angeles, in 1994.

In 1983, he joined Samsung Electronics Company, Ltd., Korea, where he was involved in the development of DRAMs, ranging from 64-kb to 4-Gb densities. Currently, he is a Senior Vice President responsible for the research and development of next-generation memory technologies for DRAM, nonvolatile memory, static random access memory, and emerging new memories such as ferroelectric random access memory, phase-change random access memory, and magnetoresistive random access memory. He was a Project Leader for the development of the world's first 1-Gb DRAM using 0.18- μm CMOS technologies during 1994–1996. He was a Technical Director for 4-Gb DRAM development during 1998–1999. He was a Program Director for 0.13- μm DRAM technology generation from its development at the R&D center to transference to manufacturing lines during 1999–2001. His current major activity is focused on the development of technologies for low-power and high-performance multigigabit density DRAMs and high-density nonvolatile memories. His research interests are memory device reliability, yield modeling on memory device, memory cell technology, and multilevel metallization for high performance of multigigabit memory devices. He has published more than 260 technical papers in the field of memory technology. He holds 70 patents related to memory technology.

Dr. Kim twice received the Grand Prize of the Samsung group for the successful development of 1-Mb DRAM and 1-Gb DRAM, in 1986 and 1996, respectively. He was a recipient of the Institute for Scientific Information (ISI)'s Citation Award for a highly cited paper. He plays an active part in advancing future memory technology through participating in panel discussions of prime conferences such as the Very Large Scale Integration Technology Symposium. He served as a committee member of the International Electron Devices Meeting, and he is a member of the editorial advisory board of *Microelectronics Reliability*. He is a Samsung Fellow.

Dae M. Kim received the B.S. degree from Seoul National University, Seoul, Korea, and the M.S. and Ph.D. degrees from Yale University, New Haven, CT, all in physics.

He was a Research Associate with the Massachusetts Institute of Technology, Cambridge, and taught at three levels of professorship with the Department of Electrical and Computer Engineering, Rice University, Houston, TX, from 1970 to 1984. After working as a Principal Scientist at Tektronix, Inc., he became a Professor with the Department

of Electronics and Electrical Engineering, Pohang University of Science and Technology (POSTECH), serving as the Chairman of the department and the Dean of the Graduate School. Currently, he is a Professor in the Computational Sciences Division, Korea Institute for Advanced Study (KIAS), Seoul. His current research interests are in Flash electrically erasable programmable read-only memory technology, nano-CMOS devices, and Schottky contacts in molecular and CNT devices.

Dr. Kim is a member of American Physical Society and a Fellow of Korean Academy of Science and Technology.