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Degradation of inversion layer electron mobility due to interface traps in metal-oxide-semiconductor transistors

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Degradation of inversion layer electron mobility during Fowler–Nordheim electron injection has been investigated using n-channel metal-oxide-semiconductor transistors. The change of the reciprocal effective mobility, $\Delta(1/\mu_{\mathrm{EFF}})$, has been found to be linearly related to the generated interface trap density, ΔN_{it}, at a given effective electric field normal to the Si/SiO$_2$ interface. The effect of trapped charges in the oxide on the mobility degradation is rather insignificant, which is attributed to the location of trapped charges from the Si/SiO$_2$ interface. The dependence of mobility degradation on inversion layer electron density has also been explained using a transport theory based on two-dimensional electron gas. © *1995 American Institute of Physics.*

I. INTRODUCTION

The increased channel and oxide electric fields in scaled metal-oxide-semiconductor (MOS) devices impose serious limitations on the long term reliability of integrated circuits. Hot-carrier-induced degradation of MOS transistors is often characterized by (1) threshold voltage shifts caused by charge trapping in the gate oxide and interface trap generation at the Si/SiO$_2$ interface and (2) the decrease of carrier mobility (transconductance) owing to the generated interface traps and the trapped charges.

So far, several investigations on carrier mobility degradation have been reported in the literature. Sun and Plummer reported an empirical relationship for electron mobility and fixed charge density.[1] Schwarz and Russek presented a model to describe electron mobility taking into account the influence of carrier screening in the inversion channel.[2] Investigations on mobility degradation after Fowler–Nordheim (FN) electron injection from the inversion channel as well as the gate electrode have been carried out in recent years.[3–6] Mobility degradation after substrate-hot-electron injection has also been reported.[7] However, many of the investigations have been discussed with empirical approaches using fitting parameters.

In order to clarify physical mechanisms of the mobility degradation due to generated interface traps and trapped charges, several transport theories for inversion electrons in MOS devices have been reported.[8–13] Brews proposed a carrier mobility model in MOS devices taking into account potential fluctuations at the Si/SiO$_2$ interface,[8,9] neglecting the dependence of carrier mobility on effective field normal to the Si/SiO$_2$ interface.[1,4] Sah *et al.* reported the close relation between electron mobility and oxide charges generated during annealing at high temperature, using a classical two-dimensional model.[10] Ando *et al.*[11] and Masaki *et al.*[12,13] calculated electron mobility in undegraded MOS devices using a quantized two-dimensional electron gas model and successfully derived the dependence of carrier mobility on effective field normal to the Si/SiO$_2$ interface.

The aim of this study is to clarify a mechanism of mobility degradation in the inversion layer of n-channel MOS transistors due to the interface traps generated during FN electron injection. The effect of charge trapping in the oxide is also investigated in this connection. The mobility degradation is evaluated under given fields or constant inversion electron densities. In addition, the experimental results are compared with the results calculated using the transport theory of quantized two-dimensional electron gas.

Experimental details are given in Sec. II, including the method to obtain generated interface trap density and trapped charge density derived from the change in I_D-V_G characteristic during FN stress. In Sec. III, the experimental results are presented and compared with the calculated results. Finally, a few conclusive statements are given in Sec. IV.

II. EXPERIMENTS

The samples used in this study are n-channel MOS transistors with a gate length, $L=2$ μm and a gate width, $W=20$ μm, fabricated on (100) p-type Si substrate with a complementary MOS process. The gate oxide with a thickness of T_{OX} = 7.7 nm is grown at 850 °C in dry O$_2$ / HCl ambient. Activation anneal of implanted impurity ions is carried out for 10 min at 900 °C in N$_2$ ambient. The average channel doping density, N_A, is 1.5×10^{17} cm^{-3}. The channel current flows parallel to the $\langle110\rangle$ direction.

Uniform degradation of the oxide and the Si/SiO$_2$ interface are achieved using FN electron injection from either the gate electrode or the inversion channel into the gate oxide. Gate current during the FN electron injection is monitored to obtain injected electron density, while I_D-V_G characteristics at $V_D=50$ mV are measured intermittently after interrupting the FN electron injection.

We use the method proposed by McWhorter and Winokur[14] to estimate trapped charge density, ΔN_{ot}, and generated interface trap density, ΔN_{it}. These values are evaluated from I_D-V_G characteristics using the formulas

$$\Delta N_{\mathrm{ot}}=\frac{C_{\mathrm{OX}}}{q}\,\Delta V_{\mathrm{MG}} \tag{1}$$

and

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[a] Also at Central Research Laboratories, Sharp Corporation, Ichinomoto-cho, Tenri-shi, Nara 632, Japan.

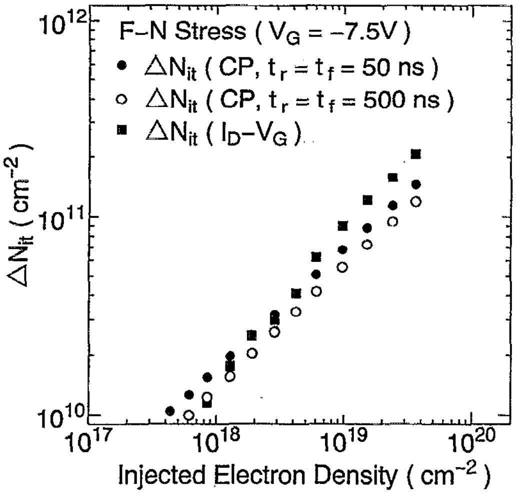

FIG. 1. Generated interface trap density, ΔN_{it}, vs injected electron density during FN electron injection from the gate electrode ($V_G = -7.5$ V). The closed squares show the result extracted from $I_D - V_G$ data. Open and closed circles show the results from CP measurements with two different values for rise and fall time (t_r, t_f).

$$\Delta N_{\text{it}}=\frac{C_{\text{OX}}}{q}(\Delta V_{\text{TH}}-\Delta V_{\text{MG}}), \tag{2}$$

where C_{OX} is the gate oxide capacitance per unit area, ΔV_{TH} is the threshold voltage shift due to generated interface traps (acceptor-type for n-channel) and trapped charges, and ΔV_{MG} is the midgap-voltage shift due to trapped charges. The midgap voltage V_{MG} is calculated from $I_D - V_G$ characteristics using the formula[15]

$$I_D|_{V_G=V_{\text{MG}}}=\mu\frac{W}{2L}\frac{qN_AL_D}{\beta}\left(\frac{n_i}{N_A}\right)^2 \times e^{\beta\Phi_F}(\beta\Phi_F)^{-1/2}(1-e^{-\beta V_D}), \tag{3}$$

where L_D is the Debye length given by $L_D=(2\kappa_S\epsilon_0/\beta qN_A)^{1/2}$, $\beta=q/k_BT$, n_i is the intrinsic carrier concentration, κ_S is the relative dielectric constant of Si, μ is the electron mobility, and $\Phi_F=(k_BT/q)\ln(N_A/n_i)$. The value of $\mu W/L$ is extracted from the maximum transconductance at V_D = 50 mV. Since the midgap current, $I_D|_{V_G=V_{\text{MG}}}$, is in the range of 0.01–0.1 pA, the linear extrapolation of the subthreshold curve ($\log I_D - V_G$) down to this low current level yields the midgap voltage V_{MG}. Negative midgap voltage shift indicates hole trapping in the oxide.

Figure 1 shows the generated interface trap density thus evaluated as a function of the injected electron density. The generated interface trap density measured with the charge pumping (CP) method[16] is also presented in the same figure. For the CP current measurements, a 100 kHz rectangular voltage with an amplitude of 3.5 V and different rise and fall times (t_r and t_f) are used. Figure 1 shows that the measured interface trap densities are higher for the applied voltage with shorter rise and fall times. This can be explained in the following way: the CP current is caused by carrier recombination through interface traps existing within about ± 0.3 eV around the midgap level. It is quite understandable that the recombination event is higher for shorter rise and fall times. As a consequence, measured CP currents are higher for shorter rise and fall times, which results in a higher value of interface trap density. Again, slight disagreement between the generated interface trap densities evaluated from the $I_D - V_G$ data and CP currents lies in the fact that the $I_D - V_G$ characteristic estimates the interface traps above the midgap level (i.e., acceptor-type interface traps only): the disagreement thus originates from the difference in the measured energy range.

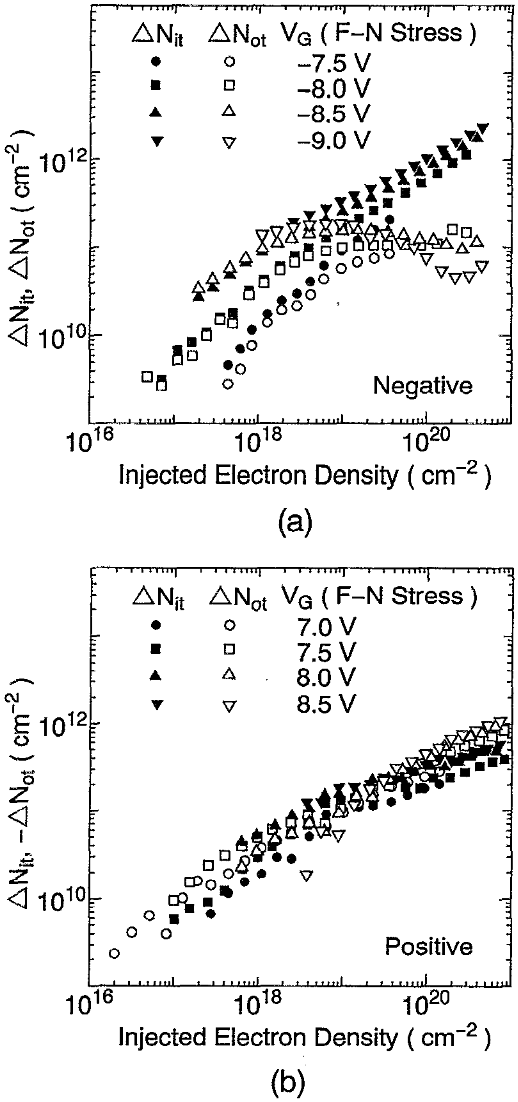

FIG. 2. Trapped charge density ΔN_{ot} (open marks) and generated interface trap density ΔN_{it} (closed marks) during FN electron injection from (a) the gate electrode (negative stress gate bias) and (b) the inversion channel (positive stress gate bias), as a function of injected electron density.

The effective mobility μ_{EFF} is derived from $I_D - V_G$ data using the formula

$$\mu_{\text{EFF}}=\frac{L}{W}\frac{g_D}{qN_{\text{inv}}}\bigg|_{V_D=\text{const}}, \tag{4}$$

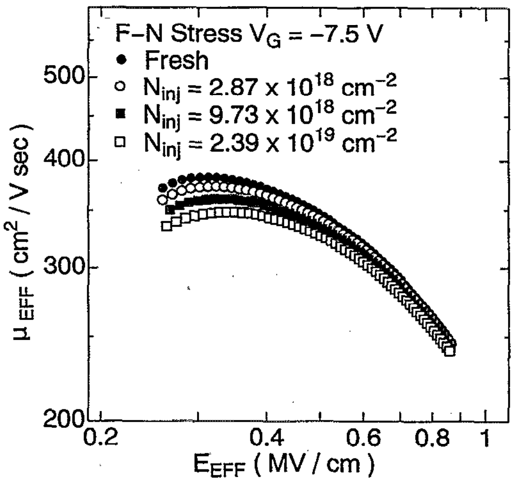

FIG. 3. Evolutions of the effective mobility vs effective field E_{EFF} during FN electron injection from the gate electrode ($V_G=-7.5$ V) with injected electron density N_{inj} as a parameter.

where $g_D=I_D/V_D$ is the channel conductance and $N_{\mathrm{inv}}=(C_{\mathrm{OX}}/q)(V_G-V_{\mathrm{TH}}-V_D/2)$ is the average inversion electron density in the channel. For simplicity, we evaluate μ_{EFF} and N_{inv} in the strong inversion region by the use of the above relations. The effective field E_{EFF} normal to the Si/SiO$_2$ interface is given by

$$E_{\mathrm{EFF}}=(\tfrac{1}{2}qN_{\mathrm{inv}}+Q_{\mathrm{depl}})/\kappa_S\epsilon_0, \qquad (5)$$

where Q_{depl} is the depletion layer charge per unit area.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the trapped charge density, ΔN_{ot}, and the interface trap density, ΔN_{it}, generated during the FN electron injection as a function of the injected electron density, N_{inj}. Electrons are injected from the gate electrode (Fig. 2(a)) and the inversion channel (Fig. 2(b)). As shown in Fig. 2(a), both the interface trap density and the trapped hole density increase linearly with injected electron density up to 10^{18} cm^{-2}, and then the trapped hole density tends to level off above $N_{\mathrm{inj}}=10^{18}$ cm^{-2}. For $N_{\mathrm{inj}}\geqslant 10^{19}$ cm^{-2}, trapped hole density tends to saturate due to a simultaneous occurence of hole trapping and neutralization of trapped holes by electron capture. Figure 2(a) also shows that both the generated interface trap density and the trapped hole density strongly depend on the stress gate voltage for injected electron density, $N_{\mathrm{inj}}\leqslant 10^{19}$ cm^{-2}. On the other hand, in the case of the FN injection from the inversion channel, as shown in Fig. 2(b), both the interface trap density and the trapped electron density increase monotonically up to $N_{\mathrm{inj}}=10^{21}$cm^{-2}. Again, the difference in trapping behavior between Figs. 2(a) and 2(b) is due to the trapping of the different type of carriers (i.e., holes and electrons). Moreover, the FN injection from the inversion channel generates neutral electron traps at the Si/SiO$_2$ interfacial region which strongly affect the electron trapping behavior.[19,20]

Figure 3 presents the degradation of the effective mobility μ_{EFF} as a function of effective field E_{EFF} with injected electron density as a parameter. Mobility degradation is significant in low effective fields where ionized impurity scattering is dominant. On the other hand, small mobility degradation in high effective fields, where interface roughness scattering is dominant, is attributed to the screening of interface traps and trapped charges by the inversion layer electrons. These results indicate that the mobility degradation by interface traps and trapped charges strongly depend on the effective field normal to the Si/SiO$_2$ interface or the inversion electron density.

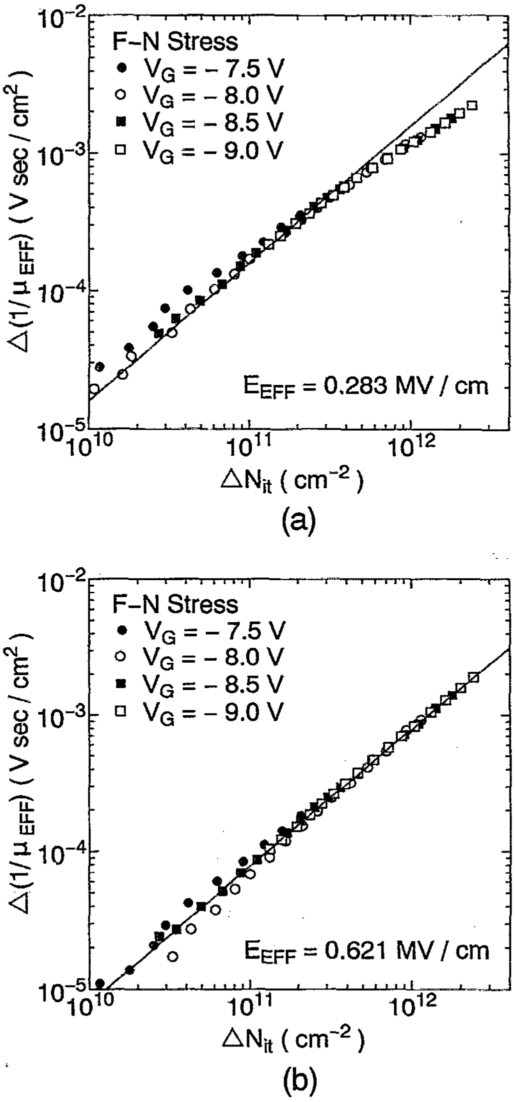

FIG. 4. $\Delta(1/\mu_{\mathrm{EFF}})$ as a function of generated interface trap density ΔN_{it} at (a) $E_{\mathrm{EFF}}=0.283$ MV/cm and (b) 0.621 MV/cm. The solid lines are the results fitted to the data of $\Delta N_{\mathrm{it}}\leqslant 4\times 10^{11}$ cm^{-2}.

Degradation of the effective mobility by the generated interface traps and the trapped charges during FN stress can be extracted from the experimental data using the following approximation:

$$\Delta\left(\frac{1}{\mu_{\mathrm{EFF}}}\right)=\frac{1}{\mu_{\mathrm{EFF}}}\bigg|_{\mathrm{degraded}}-\frac{1}{\mu_{\mathrm{EFF}}}\bigg|_{\mathrm{fresh}}. \qquad (6)$$

Figures 4(a) and 4(b) show $\Delta(1/\mu_{\mathrm{EFF}})$ at $E_{\mathrm{EFF}}=0.283$

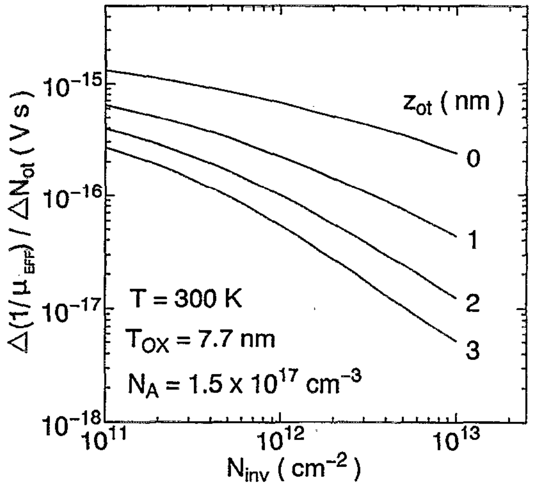

FIG. 5. Calculated $\Delta(1/\mu_{EFF})/\Delta N_{ot}$ vs inversion layer electron density N_{inv} with the distance of Coulomb scattering centers from the Si/SiO$_2$ interface z_{ot} as a parameter.

MV/cm and 0.621 MV/cm as a function of the generated interface trap density, ΔN_{it} after the FN electron injection from the gate electrode. There exists a linear relationship between $\Delta(1/\mu_{EFF})$ and ΔN_{it} for $\Delta N_{it} \leq 4 \times 10^{11}$ cm^{-2} (as shown in Figs. 4(a) and 4(b)). However, slight deviation from the linearity over $\Delta N_{it} = 4 \times 10^{11}$ cm^{-2} in Fig. 4(a), can be explained as multiple scattering[17,18] due to charged interface traps since the screening length due to inversion layer electrons is larger than $N_{it}^{-1/2}$ at low effective field. Similar experimental results are also observed for the FN electron injection from the inversion channel.

In the following discussion, we consider mobility degradation for the FN electron injection only from the gate electrode for simplicity. Based on the experimental evidence that the trapped charges behave differently from the generated interface traps for injected electron density above 10^{18} cm^{-2}, as shown in Fig. 2(a), it can be concluded that trapped charges in the oxides do not affect $\Delta(1/\mu_{EFF})$; charge trapping ceases for injected electron density over 10^{19} cm^{-2} (see Fig. 2(a)) while $\Delta(1/\mu_{EFF})$ increases monotonically. The scarce dependence of effective mobility on the trapped charge density can be attributed to the separation of trapped charges from the inversion layer electrons. It has been reported that a negligible amount of trapped charges exist within 2–3 nm from the Si/SiO$_2$ interface due to a spontaneous tunneling discharging of the trapped charges.[23–25]

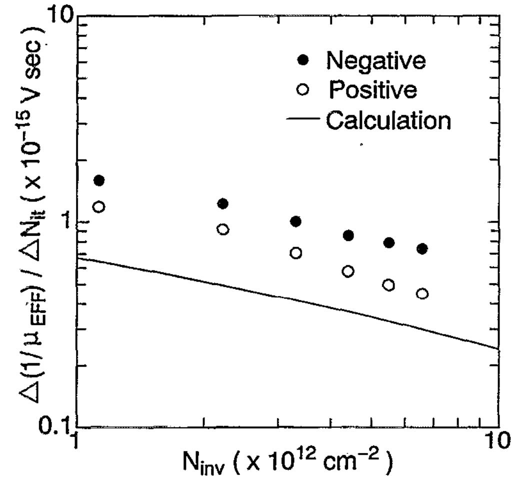

FIG. 6. $\Delta(1/\mu_{EFF})/\Delta N_{it}$ as a function of inversion layer electron density ΔN_{inv}. Open and closed circles show the experimental results from FN electron injection stress from the inversion channel (positive stress gate bias) and the gate electrode (negative stress gate bias), respectively. Solid curve shows the calculated results.

In order to explain the experimental results of mobility degradation, we calculated $\Delta(1/\mu_{EFF})/\Delta N_{ot}$ as a function of inversion layer electron density, N_{inv}, with the distance of Coulomb scattering centers from the Si/SiO$_2$ interface, z_{ot}, as a parameter, based on the transport theory of two-dimensional electron gas.[11] In the calculation, the wave function of the inversion layer electron in the normal direction to the Si/SiO$_2$ interface is assumed to be given by the Fang–Howard trial function[26,27] for simplicity. Inversion layer electrons are assumed to be scattered with the charged interface traps and the trapped charges. The carrier screening effect by inversion layer electrons is included.[28] Details of mobility degradation due to trapped charges and charged interface traps are presented in the Appendix. Figure 5 shows calculated $\Delta(1/\mu_{EFF})/\Delta N_{ot}$ vs inversion electron density with z_{ot} as a parameter. The figure demonstrates negligible mobility degradation for trapped charges situated over $z_{ot}=2$ nm in comparison to charged interface traps ($z_{ot}=0$).

The difference between Figs. 4(a) and 4(b) by a factor of two can be interpreted as the increase of the effective field or the inversion layer electron density reduces electron scattering by charged interface traps because of the screening effect due to inversion layer electrons. In this connection, we calculated $\Delta(1/\mu_{EFF})/\Delta N_{it}$ from the slopes of the experimental results similar to those as shown in Figs. 4(a) and 4(b). The results thus obtained are plotted as a function of inversion layer electron density as presented in Fig. 6. Theoretically calculated $\Delta(1/\mu_{EFF})/\Delta N_{it}$ is also shown in this figure as a function of inversion layer electron density. $\Delta(1/\mu_{EFF})/\Delta N_{it}$ extracted from the experimental results is nearly proportional to $N_{inv}^{-1/4}$, which agree qualitatively with the theoretical calculation. This explains that the dependence of mobility degradation on the inversion electron density is mainly caused by the variation of the Coulomb potential due to the screening effect by inversion layer electrons. The quantitative disagreement between theoretical and experimental results originates from the fact that the experimental techniques used in this study underestimate the generated interface trap density.

IV. CONCLUSIONS

Degradation of inversion layer electron mobility due to interface traps generated during FN electron injection has been investigated using n-channel MOS transistors. Inverse of effective mobility degradation, $\Delta(1/\mu_{EFF})$, is found to be proportional to the generated interface trap density ΔN_{it} at a given effective electric field normal to the Si/SiO$_2$ interface. However, in low effective normal fields, slight deviation from the relation for high interface trap density is observed. This is due to the fact that the screening length in low effective fields is larger than $N_{\rm it}^{-1/2}$, causing multiple scattering due to charged interface traps. The contribution of trapped charges in the oxide to mobility degradation is found to be insignificant. The transport theory of two-dimensional electron gas explains that the negligible mobility degradation caused by trapped charges is attributed to the location ($z_{\rm ot} \geqslant 2$ nm), and that $\Delta(1/\mu_{\rm EFF})/\Delta N_{\rm it}$ is proportional to $N_{\rm inv}^{-1/4}$.

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APPENDIX

The expression for mobility degradation due to trapped charges and charged interface traps is derived assuming the Coulomb interaction. In the calculation, we use the transport theory of two-dimensional electron gas.[11] For simplicity, inversion layer electrons are assumed to occupy one ground subband E_0, in which the wave function in the direction normal to the Si/SiO$_2$ interface is given by the Fang–Howard trial function.[26,27]

The momentum relaxation time of inversion layer electrons for scattering due to trapped charges is given by

$$\frac{1}{\tau_{\rm ot}(k)}=\frac{m_d^* q^4 N_{\rm ot}}{4\pi\hbar^3\bar{\kappa}^2\epsilon_0^2}\int_0^\pi \frac{J(Q(\theta),z_{\rm ot})(1-\cos\theta)}{[Q(\theta)+P(Q(\theta))H(Q(\theta))]^2}\,d\theta, \tag{A1}$$

where

$$Q(\theta)=2k\,\sin\frac{\theta}{2}, \tag{A2}$$

$$\bar{\kappa}=\frac{\kappa_{\rm S}+\kappa_{\rm OX}}{2}, \tag{A3}$$

$$J(Q,z_{\rm ot})=\left|\int_0^\infty |\xi(z)|^2\exp(-Q|z+z_{\rm ot}|)dz\right|^2, \tag{A4}$$

$$H(Q)=\frac{1}{2}\int_0^\infty dz_1\int_0^\infty dz_2|\xi(z_1)|^2|\xi(z_2)|^2 \times\left[\left(1+\frac{\kappa_{\rm OX}}{\kappa_{\rm S}}\right)\exp(-Q|z_1-z_2|) +\left(1-\frac{\kappa_{\rm OX}}{\kappa_{\rm S}}\right)\exp(-Q|z_1+z_2|)\right], \tag{A5}$$

$$P(Q)=\frac{q^2}{2\bar{\kappa}\epsilon_0}\frac{m_d^* n_v}{\pi\hbar^2}\left[f(E_0) +\int_0^{\epsilon_{Q/2}}\sqrt{1-\frac{\epsilon}{\epsilon_{Q/2}}}\,\frac{df(E_0+\epsilon)}{d\epsilon}\,d\epsilon\right], \tag{A6}$$

$$\epsilon_{Q/2}=\frac{\hbar^2}{2m_d^*}\left(\frac{Q}{2}\right)^2, \tag{A7}$$

m_d^* is the density-of-states effective mass of Si, n_v is the number of valley, $\kappa_{\rm OX}$ and $\kappa_{\rm S}$ are the relative dielectric constants of SiO$_2$ and Si, respectively, and $f(E)$ is the Fermi–Dirac distribution function. We can assume $m_d^*=m_t^*$ for inversion layer electrons at the (100) interface. Equation (A6) is derived from the method of Maldague,[28] where the dielectric function at finite temperatures is derived from that at zero temperature. Profiles of trapped charges are assumed to be a δ function in the normal direction to the Si/SiO$_2$ interface.

The contribution of trapped charges to electron mobility is given by

$$\mu_{\rm ot}=\frac{q}{m^*}\frac{\langle\tau_{\rm ot}(k(\epsilon))\epsilon\rangle}{\langle\epsilon\rangle}, \tag{A8}$$

where m^* is conductive effective mass of Si ($m^*=m_t$ for the E_0 subband), ϵ is the electron energy measured from E_0, $k(\epsilon)=\sqrt{2m^*\epsilon}/\hbar$, and the average of function $g(\epsilon)$ on ϵ, $\langle g(\epsilon)\rangle$, is defined as

$$\langle g(\epsilon)\rangle=\int_0^\infty g(\epsilon)\frac{df(\epsilon+E_0)}{d\epsilon}\,d\epsilon. \tag{A9}$$

Based on the above equations, the mobility degradation due to trapped charges is given by

$$\Delta\left(\frac{1}{\mu_{\rm EFF}}\right)=\frac{m_d^* m^* q^3\Delta N_{\rm ot}}{4\pi\hbar^3\bar{\kappa}^2\epsilon_0^2}\langle\epsilon\rangle \times\left\langle\frac{\epsilon}{\int_0^\pi\frac{J(Q(\theta),z_{\rm ot})(1-\cos\theta)}{[Q(\theta)+P(Q(\theta))H(Q(\theta))]^2}\,d\theta}\right\rangle^{-1}. \tag{A10}$$

For mobility degradation due to charged interface traps, we use $\Delta N_{\rm it}$ in place of $\Delta N_{\rm ot}$ and set $z_{\rm ot}=0$ in Eq. (A10).

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