Surface Roughness Scattering in Ultrathin-Body SOI MOSFETs

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Abstract

A rigorous surface roughness scattering model for ultrathin-body SOI MOSFETs is presented, which extends Ando's model for bulk MOSFETs. The matrix element of the scattering potential includes a generalized Prange-Nee term and all the Coulomb interaction terms. Using this model, we study the effects of the silicon body thickness, effective field, and dielectric constant of the insulator on the roughness-limited low-field electron mobility in ultrathin-body SOI MOSFETs.

1 Introduction

The low-field electron mobility of ultrathin-body silicon-on-insulator (UTBSOI) MOSFETs shows a strong dependence on the body thickness t_s [1, 2]. In particular, for an extremely thin Si body the mobility is almost proportional to t_s^6, which is attributed to the surface roughness (SR) scattering [2] and can be an important factor limiting the scaling of UTBSOI MOSFETs.

Previous SR scattering models for UTBSOI MOSFETs only consider the Prange-Nee term [3, 4] caused by the roughness-induced deformation of wavefunctions. In this work, we take into account all the additional Coulomb interaction terms first proposed by Ando [5]. Contrary to the Ando's model, the matrix element is derived for UTBSOI MOSFETs where the body thickness is finite, which reduces to Ando's expression in the limit of $t_s \to \infty$. The matrix element reflecting the deformation of wavefunctions is expressed in an integral form which can be recognized as a generalized Prange-Nee term because those two expressions are equivalent in the limit of an infinitely high insulator-semiconductor barrier while our integral form gives more accurate results in the case of a finite barrier-height than the original Prange-Nee expression. The matrix element reflecting the Coulomb interactions is originated from the roughness-induced fluctuation of the electron charge density, of the interface polarization charge, and of the image-charge density. Screening effects are also taken into account within the random phase approximation. We summarize the expressions for the matrix element in Fig. 1. The meaning and detailed derivation of these expressions are explained in [6]. We calculate the SR-limited low-field electron mobility in single gate UTBSOI MOSFETs at room temperature using the self-consistent solution of the Schrödinger and Poisson equations and the Kubo-Greenwood formula. Effects of (uncorrelated) roughness at both the top and bottom interfaces are included in the simulation.

Matrix element for surface roughness scattering $V^{\mathrm{SR}}_{n\mathbf{k}n'\mathbf{k}'} = \left[\Gamma^{\mathrm{GPN}}_{nn'} + \Gamma^{\mathbf{q}}_{nn'}\right]\Delta_{\mathbf{q}}$

Generalized Prange-Nee term

$$\Gamma^{\mathrm{GPN}}_{nn'} = (E_n - E_{n'}) \int dz \zeta_n \left(1 - \frac{z}{t_s}\right)\frac{\partial \zeta_{n'}}{\partial z} + \int dz \zeta_n \left[-\frac{\hbar^2}{t_s}\frac{\partial}{\partial z}\frac{1}{m_z}\frac{\partial}{\partial z} + \frac{\partial V}{\partial z}\left(1 - \frac{z}{t_s}\right)\right]\zeta_{n'}$$

Coulomb terms

$$\Gamma^{\mathbf{q}}_{nn'} = \int dz \zeta_n(z)\left[V^{\mathrm{n}}_{\mathbf{q}}(z) + V^{\sigma}_{\mathbf{q}}(z) + V^{\mathrm{im}}_{\mathbf{q}}(z)\right]\zeta_{n'}(z)$$

$$V^{\mathrm{n}}_{\mathbf{q}}(z) = -\frac{e^2}{\epsilon_{si}}\int dz' G_{\mathbf{q}}(z,z')\left[\left(\frac{z'}{t_s} - 1\right)\frac{\partial n(z')}{\partial z'} + \frac{n(z')}{t_s}\right] \quad \text{(shift of charge-sheet)}$$

$$V^{\sigma}_{\mathbf{q}}(z) = e\tilde{\epsilon}F_s \frac{e^{-qz} + \tilde{\epsilon}e^{qz-2qt_s}}{1-\tilde{\epsilon}^2 e^{-2qt_s}} \quad \text{(dipoles at step)}$$

$$V^{\mathrm{im}}_{\mathbf{q}}(z) = \frac{e^2\tilde{\epsilon}}{8\pi^2}\int \frac{d\mathbf{k}}{\epsilon_{si}+\epsilon_{ox}}\left[\frac{\epsilon_{ox}}{\epsilon_{si}} + \frac{\mathbf{k}\cdot\mathbf{k}'}{kk'}\right]\left[\frac{e^{-kz}+\tilde{\epsilon}e^{kz-2kt_s}}{1-\tilde{\epsilon}^2e^{-2kt_s}}\right]\left[\frac{e^{-k'z}+\tilde{\epsilon}e^{k'z-2k't_s}}{1-\tilde{\epsilon}^2e^{-2k't_s}}\right]$$

(image charge fluctuation)

Figure 1: Matrix element for the surface roughness scattering.

2 Simulation Results

Fig. 2 shows the low-field mobility as a function of silicon body thickness. The mobility exhibits a strong t_s^6-like thickness dependence as $t_s \longrightarrow 0$ especially when the electron density is low. Also, it converges to the mobility of bulk MOSFETs when $t_s \longrightarrow \infty$. Fig. 3 (a) shows the SR-limited mobility as a function of the effective field for different silicon body thickness. The dependence of the SR-limited mobility on the effective field weakens as t_s becomes smaller because the kinetic energy fluctuation due to the structural confinement becomes more important. In Fig. 3 (b), we plot separately the SR-limited mobility due to the (generalized) Prange-Nee term, to the Coulomb interaction term, and to both terms. Although the contribution of the Coulomb interaction term is smaller than the Prange-Nee term, the Coulomb interaction term is not negligible since it reduces the mobility about 50% with respect to the mobility limited by the Prange-Nee term only. Also, the screening effect makes the mobility increase slightly as the field increases in the low effective-field region. Fig. 4 shows the effects of the dielectric constant on the surface roughness scattering limited mobility. The mobility increases as the dielectric constant increases because the Coulomb term cancels the Prange-Nee term when the dielectric constant of the insulator is larger than that of semiconductor.

3 Conclusion

We have presented a rigorous surface-roughness scattering model for UTBSOI MOSFETs. The mobility shows the expected t_s^6-like dependence. The Coulomb interaction, which has been usually neglected so far, actually affects the mobility significantly. Interestingly, the SR-limited mobility increases in high-κ materials due to the Coulomb interaction if the surface quality remains the same.

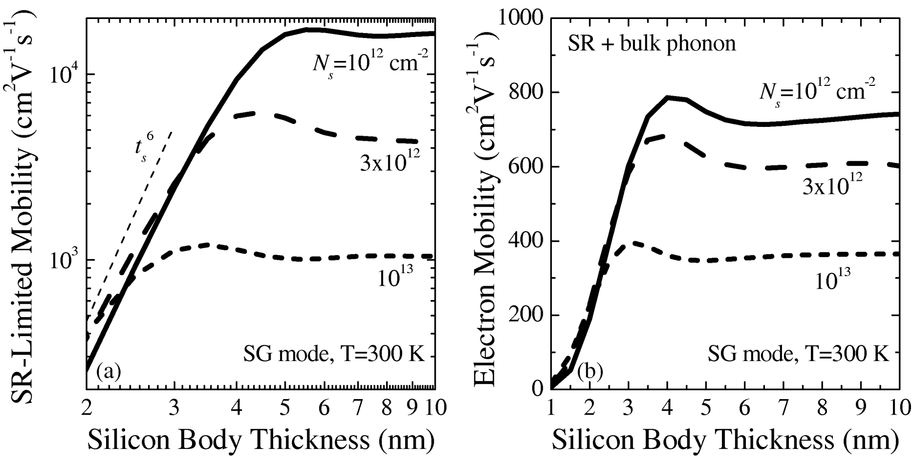

Figure 2: Calculated low-field mobility of UTBSOI MOSFETs as a function of the silicon body thickness. Fig. 2 (a) shows the mobility limited by the surface roughness scattering and (b) shows the mobility limited by the surface roughness and bulk phonon scattering.

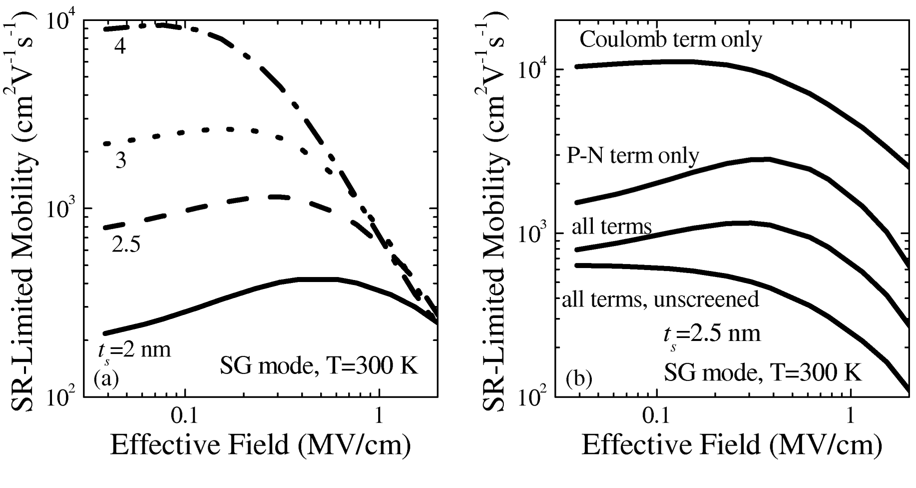

Figure 3: Effects of the effective field on the surface roughness scattering limited mobility of UTBSOI MOSFETs. Fig. 3 (a) shows the SR-limited mobility as a function of effective field for four different silicon body thickness and (b) shows the contribution of the Coulomb interaction term, generalized Prange-Nee term, and screening.

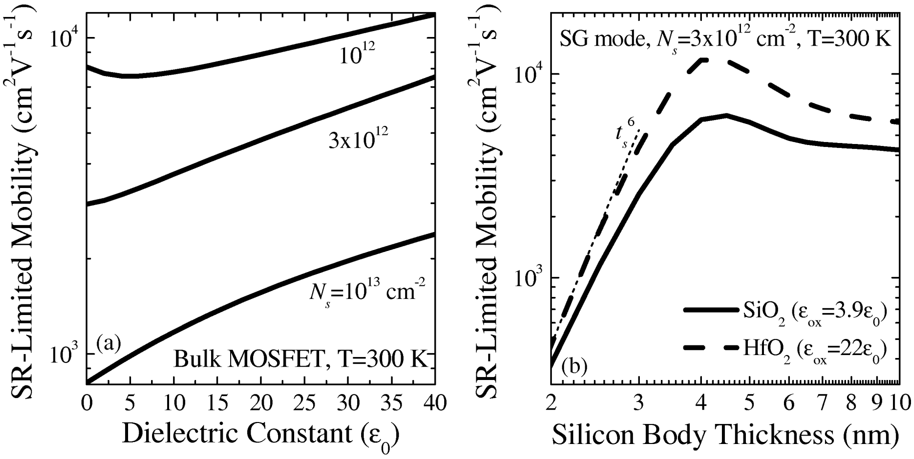

Figure 4: Effects of the dielectric constant on the surface roughness scattering limited mobility. Fig. 4 (a) shows the SR-limited mobility of bulk MOSFETs as a function of the dielectric constant and (b) shows the mobility as a function of silicon body thickness for different dielectric materials (SiO_2 and HfO_2), where the same surface roughness parameters are used.

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References

[1] D. Esseni, M. Mastrapasqua, G. K. Celler, C. Fiegna, L. Selmi, and E. Sangiorgi, "Low field electron and hole mobility of SOI transistors fabricated on ultrathin silicon films for deep submicrometer technology application," *IEEE Trans. Electron Devices*, vol. 48, no. 12, pp. 2842–2850, Dec. 2001.

[2] K. Uchida, H. Watanabe, A. Kinoshita, J. Koga, T. Numata, and S. Takagi, "Experimental study on carrier transport mechanism in ultrathin-body SOI n- and p-MOSFETs with SOI thickness less than 5 nm," in *International Electron Devices Meeting Tech. Digest*, San Francisco, Dec. 2002, pp. 47 – 50.

[3] R. E. Prange and T.-W. Nee, "Quantum spectroscopy of the low-field oscillations in the surface impedance," *Phys. Rev.*, vol. 168, no. 3, pp. 779–786, Apr. 1968.

[4] D. Esseni, "On the modeling of surface roughness limited mobility in SOI MOSFETs and its correlation to the transistor effective field," *IEEE Trans. Electron Devices*, vol. 51, no. 3, pp. 394–401, Mar. 2004.

[5] T. Ando, A. B. Fowler, and F. Stern, "Electronic properties of two-dimensional systems," *Reviews of Modern Physics*, vol. 54, no. 2, pp. 437–672, Apr. 1982.

[6] S. Jin, M. V. Fischetti, and T.-w. Tang, "Modeling of surface roughness scattering in ultrathin-body SOI MOSFETs," *IEEE Trans. Electron Devices, in press*, Aug. 2007.