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Phonon Limited Electron Transport In SOI and Double-Gate MOSFETs Incorporating Realistic Acoustic Phonon Waves

Shigeyasu Uno[a)] and Nobuya Mori [b)]
[a)] School of Mathematical Sciences, Claremont Graduate University
710 N. College Ave. Claremont, CA 91711, USA
Phone: +1-909-621-8080 Fax: +1-909-607-8261 E-mail: shigeyasu.uno@cgu.edu
[b)] Department of Electronic Engineering, Osaka University
2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

1. Introduction

When hard and soft materials are mixed, acoustic phonon waves in the resulting material behave differently than in each constitutive material. Impacts of such difference on electron transport have been investigated for III-V semiconductors [1-3] and Si MOSFETs [4]. However, no investigations have been done on the silicon-on-insulator (SOI) and the double-gate (DG) MOSFETs, in spite of its technological significance. In this work, the impact of phonon wave modulation on electron transport in such SOI-related structures is examined theoretically.

2. Phonon Modulation in SOI and DG MOSFETs

Figure 1 shows our model of the SOI-related structures mentioned above. For simplicity, the silicon plate of thickness d is assumed to be embedded in a bulk SiO_2 with infinite extent. As the system is isotropic along the Si plate, the phonon waves in the x and y directions are simply plane waves. However, this is not the case for phonon waves in the z direction due to mechanical mismatch between Si and SiO_2. Such phonon waves are categorized into three types according to their frequency ω and wave vector along x-y plain $q_{//}$. Fig. 2 shows the z component of such different types of the phonon waves.

The type (I) phonons are sinusoidal in both Si and SiO_2 region, but have different amplitudes. For the type (II) phonon, the wave form is sinusoidal in SiO_2, but decays exponentially in Si. The type (III) phonon waves decay exponentially both in Si and SiO_2. The latter two types of phonons are the interface phonons.

3. Acoustic Deformation Potential Scattering in SOI and DG MOSFETs

The acoustic deformation potential (ADP) scattering rate for an initial electron state (n, $\mathbf{K}$) reads

$$\frac{1}{\tau}=\sum_{n'}\frac{D_{\mathrm{aco}}{}^2 k_{\mathrm{B}}T_L}{2\pi\hbar v_l{}^2\rho}\int d^2\mathbf{K}'\delta\left[E_{n'}(\mathbf{K}')-E_n(\mathbf{K})\right]$$
$$\times\int\frac{L_z}{2\pi}\frac{A v_l{}^2\rho}{\omega_{\pm\mathbf{q}}{}^2}\left|\langle n'|\left\{iq_x u_x(z)+iq_y u_y(z)+\frac{\partial u_z(z)}{\partial z}\right\}|n\rangle\right|^2 dq_z,$$

where n and n' are the electron subband indices before and after the scatterings, the $\mathbf{K}$ and $\mathbf{K}'$ are the electron wave vector in the x-y plane, the q_x and q_y are the in-plane phonon wave vector components mediating the scattering, and the u_x, u_y, and u_z are the tree components of the phonon displacements. The other notations have the conventional meanings.

The terms in the parenthesis in the matrix element are equivalent to the strain caused by the phonon vibration. Fig. 3 shows the magnitude of the strain component calculated for the three types of phonon waves. Note that the strain in the Si region is less than that in bulk Si (dashed line). Instead, the strain in the oxide region is increased. This has been observed in a similar Si/SiO_2 system, and referred to as 'strain absorption effect' [5, 6]. Fig. 4 shows an integral of the strain component within Si region ($-d/2 < z < d/2$) plotted as a function of ω. This quantity gives an estimate of the magnitude of the strain. Note that the reduction of the strain component due to the strain absorption effect is seen for most of ω. Fig. 5 shows the integrand of the integral in terms of q_z (form factor) as a function of ω. The electron wave functions in an infinite square well were used, and we assumed intra-subband scattering ($n = n' =1$). The contributions from different types of phonons appear in the different ranges of ω. The overall reduction of the strain in Fig. 4 is also seen in Fig. 5, which might decrease the scattering rate. On the other hand, the appearance of the interface phonons (types (II) and (III)) increases the scattering rate. Further results on the scattering rate and mobility would be shown and discussed in the presentation.

4. Conclusion

Impact of incorporating the realistic acoustic phonon waves on electron transport in the SOI or DG MOSFETs has been discussed. The strain absorption of the oxide might reduce the scattering rate, whereas the appearance of the interface phonons has opposite effect. These two competing effects may alter the ADP scattering limited mobility obtained by assuming the bulk phonons, which could lead to modification of widely-used mobility model for DG MOSFETs.

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Reference

[1] S. M. Komirenko *et. al.*, Phys. Rev. B 62., p. 7459 (2000).
[2] B. A. Glavin *et. al.*, Phys. Rev. B 65., p. 205315 (2002).
[3] E. P. Pokatilov *et. al.*, J. Appl. Phys. 95., p. 5626 (2004).
[4] H. Ezawa, Annals of Physics 67, p. 438 (1971).
[5] S. Uno *et. al.*, SSDM 2004, H-1-5, 2004, Tokyo
[6] S. Uno *et. al.*, J. Appl. Phys. 97, p. 113506 (2005).

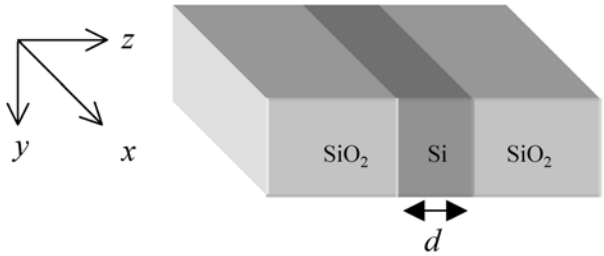

Fig. 1 The SOI (or double-gate) MOSFET model used in our calculation. The Si plate of thickness d is embedded in the infinite SiO_2 bulk. The coordinates used in this work are indicated as in this figure.

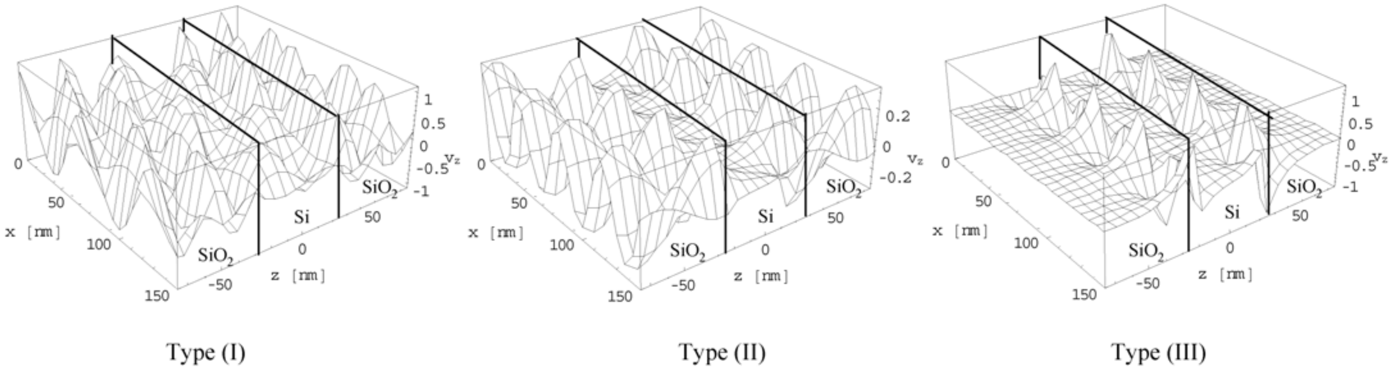

Fig. 2 The z component of the longitudinal phonon waves in SOI. Type (I) $\omega > v_{si,l}\, q_{//}$: sinusoidal, Type (II) $v_{si,l}\, q_{//} > \omega > v_{ox,l}\, q_{//}$: sinusoidal/exponential, and Type (III) $v_{ox,l}\, q_{//} > \omega$: surface mode, where $v_{si,}$ and $v_{ox,}$ are the longitudinal sound velocity in Si ($v_{si,l} = 9.0\times10^3$ m/s) and SiO_2 ($v_{ox,l} = 5.9\times10^3$ m/s). The Si thickness was set as d = 50nm.

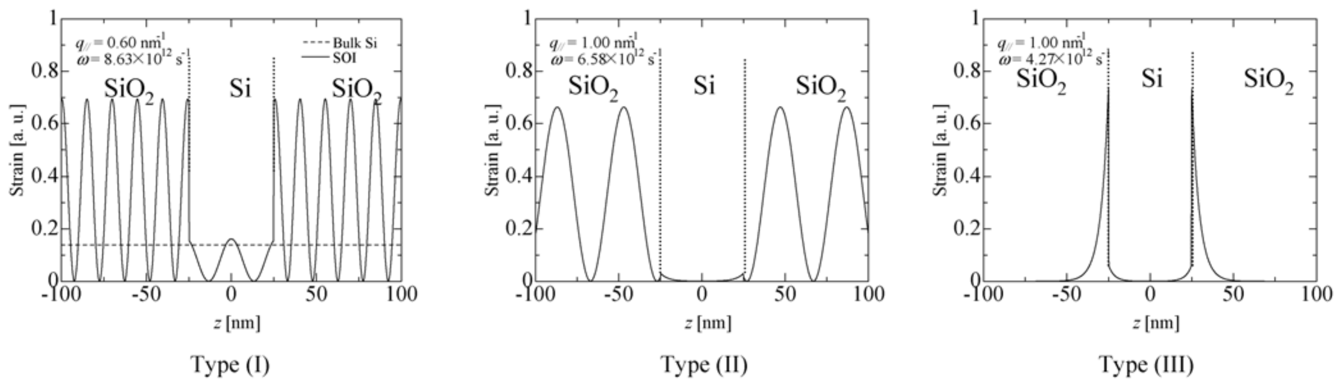

Fig. 3 Squared absolute value of the strain caused by the phonon vibrations of the type (I), (II) and (III), as a function of z. Dashed line in (I) is result of the longitudinal phonon in bulk Si having the same wave vector and energy. Note that the strain in Si region is "absorbed" by the oxide layers, as predicted in [5].

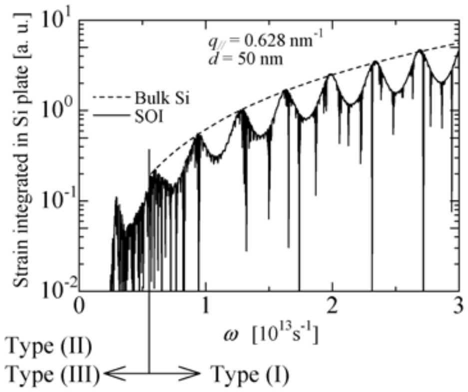

Fig. 4 The strain component integrated within the Si region ($-d/2 < z < d/2$) plotted as a function of ω. The spikes observed in the solid curves are caused by interference between longitudinal and transverse phonon modes. The three types of phonon modes appear in different ranges of ω.

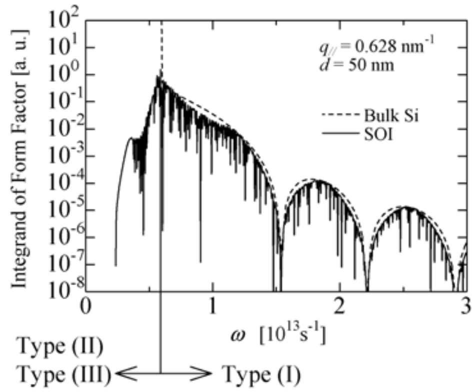

Fig. 5 The integrand of the form factor as a function of ω. The electron wave functions in an infinite square well were used, and we assumed intra-subband scattering ($n = n' = 1$). Again, contributions from different types of phonons appear in the different ranges of ω.