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Unified Roughness Scattering Model Incorporating Scattering Component Induced by Thickness Fluctuation in SOI MOSFETs

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1. Introduction

It has been reported that the inversion layer mobility exhibits a significant SOI-thickness (T_{SOI}) dependence in SOI MOSFETs [1, 2]. A scattering caused by the SOI-thickness-fluctuation (δT_{SOI}) is considered to be one of the possible origins of this dependence [3]. Although several theoretical works have been published [4, 5], δT_{SOI}-induced scattering is not fully understood yet.

In this study, we propose a unified model of roughness scattering in single-gate SOI MOSFETs. δT_{SOI}-induced scattering component is naturally derived from the proposed roughness scattering model. It is found that the experimental mobility lowering associated with thin SOI layer can be explained well by considering δT_{SOI}-induced scattering component.

2. Formulation of unified roughness scattering model

The modeling of roughness scattering in SOI MOSFETs is difficult because the wave function of the inversion layer is modulated by the interface roughness and, as a result, the fundamental assumption of Born approximation is violated. To formulate roughness scattering model in SOI MOSFETs within the framework of perturbation theory, we transform the rough interface to the flat interface by introducing the appropriate coordinate transformation (Figure 1) [6]. Thus, a rough interface barrier is transferred to a regular interface barrier and the effect of the interface irregularity is transferred from the interface barrier potential to other parts of the Hamiltonian, ΔH, which can be treated as perturbation:

$$\Delta H = \frac{\partial V_s(z)}{\partial z}\Delta_s(\mathbf{r}) + \frac{\hbar^2}{m_z}\frac{\partial^2}{\partial z^2}\frac{\delta T_{soi}(\mathbf{r})}{T_{soi}^0} + z\frac{\partial V_s(z)}{\partial z}\frac{\delta T_{soi}(\mathbf{r})}{T_{soi}^0} \quad (1)$$

The first term of r.h.s of eq. (1) is the conventional surface roughness scattering model [6]. δT_{SOI}-dependent term in eq. (1) leads to δT_{SOI}-induced scattering component and consists of the two contributions. The second term of r.h.s of eq. (1) is the contribution from the kinetic energy fluctuation and leads to the scattering component associated with the sub-band energy fluctuation [7]. The third term of eq. (1) is the contribution from the potential energy fluctuation newly found in the present study. Thus, the roughness scattering model proposed above is the unified scattering model applicable to single-gate SOI MOSFETs and includes the roughness scattering model both in bulk MOSFETs and thin SOI MOSFETs.

3. Analysis of δT_{SOI}-induced scattering component

Calculation of the inversion layer mobility in single-gate SOI MOSFETs is performed by relaxation time approximation. The 2-D subband structure is determined by solving Poisson and Schrödinger equations self-consistently. Roughness parameters (correlation length, Λ_s of 1.3nm and r.m.s value, Δ_s of 0.55nm) are determined from the fitting of the universal curve in bulk MOSFETs. The same values of roughness parameters are used for BOX surface. We examine the effect of each term in eq. (1).

It is found from Fig. 2 that the first term of r.h.s of eq. (1), ΔH_1, alone leads to the significant T_{SOI}-dependence of the mobility limited by this term, $\mu_{\Delta H_1}$ [8]. The T_{SOI}-dependence of $\mu_{\Delta H_1}$ is due to the increase of electron occupancy in the 2-fold valley in thin SOI films (Fig. 3). The thinner inversion layer thickness in the 2-fold valley than in the 4-fold valley leads to the lower $\mu_{\Delta H_1}$ in the 2-fold valley than in the 4-fold valley. Therefore, the large electron occupancy in the 2-fold valley causes the lower $\mu_{\Delta H_1}$.

Fig. 4 shows the comparison of $\mu_{\Delta H}$ limited by ΔH (all terms in eq. (1)) and $\mu_{\Delta H_1}$ limited by the first term of eq. (1). The significant contribution from δT_{SOI}-dependent term in eq. (1) is observed. We examine in Fig. 5 the effect of the third term of eq. (1), ΔH_3. The non-negligible contribution from the third term of eq. (1) in Fig. 5 indicates that the consideration of only the conventional roughness scattering components [6, 7], first and second terms of eq. (1), is not enough for the quantitative evaluation of δT_{SOI}-induced scattering component in SOI MOSFETs. As can be seen from Fig. 6, δT_{SOI}-induced scattering component in eq. (1) causes the further decrease in $\mu_{\Delta H}$ than in $\mu_{\Delta H_1}$ and, as a result, leads to strong T_{SOI} dependence.

4. Comparison with experimental results

For the comparison of the calculated results with the experimental data at room temperature, mobility limited by phonon scattering, μ_{phonon}, is also taken into account. As can be seen from Fig. 7, μ_{phonon} in thin single-gate SOI films is almost determined from that in the 2-fold valley because of the large occupancy in the 2-fold valley (Fig. 3).

Fig. 8 show the comparison of the calculated inversion layer mobility, μ_{eff}, in thin single-gate SOI films with the experimental data as a function of T_{SOI} at effective electric field (E_{eff}) of 0.6MV/cm. Contributions from both phonon scattering and roughness scattering calculated by eq. (1) are accounted for in the calculation. From Fig. 8, the first term of r.h.s of eq. (1) alone cannot fully explain the experimental T_{SOI} dependence of μ_{eff} in thin SOI films. The experimental results can be explained well by considering δT_{SOI}-induced scattering component, the second and third terms of r.h.s of eq. (1).

5. Conclusions

A unified model of roughness scattering in single-gate SOI MOSFETs has been proposed. It was found that δT_{SOI}-induced scattering component derived from this unified roughness scattering model leads to the significant T_{SOI} dependence of the inversion layer mobility in SOI MOSFETs.

It was also found that the experimental mobility lowering associated with thin SOI layer can be explained well by considering δT_{SOI}-induced scattering component.

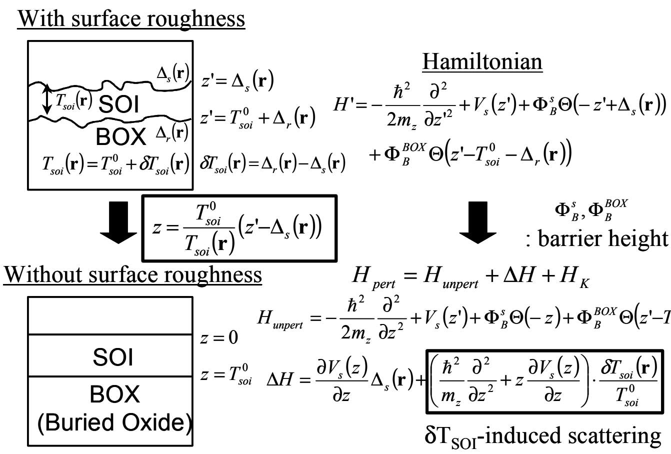

Fig. 1 Schematic diagram explaining the derivation of the δT_{SOI}-induced scattering component in SOI MOSFETs. Θ(z)=1 for z>0 and Θ(z)=0 for z<0. $V_s(z)$ is potential distribution in SOI film.

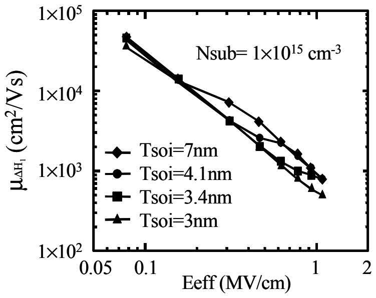

Fig. 2 E_{eff} dependence of $\mu_{\Delta H_1}$ calculated by the first term of r. h. s of eq. (1) as a parameter of T_{SOI}.

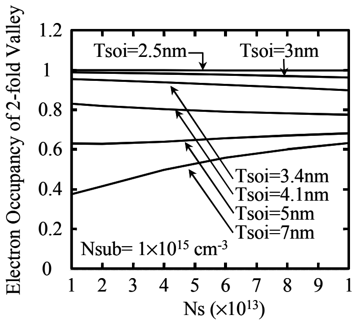

Fig. 3 Calculated N_s dependence of electron occupancies of the 2-fold valleys as a parameter of T_{SOI}.

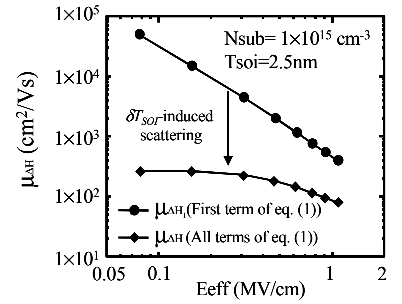

Fig. 4 Comparison of E_{eff} dependence of $\mu_{\Delta H}$ and $\mu_{\Delta H_1}$ calculated based on Eq. (1).

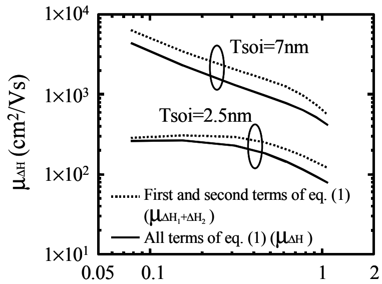

Fig. 5 E_{eff} dependence of $\mu_{\Delta H}$ with and without the third term of eq. (1) as a parameter of T_{SOI}.

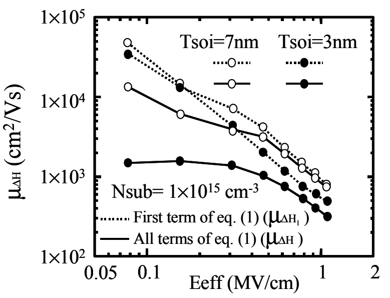

Fig. 6 E_{eff} dependence of $\mu_{\Delta H}$ limited by ΔH (all terms in eq. (1)) and $\mu_{\Delta H_1}$ limited by the first term of eq. (1) as a parameter of T_{SOI}.

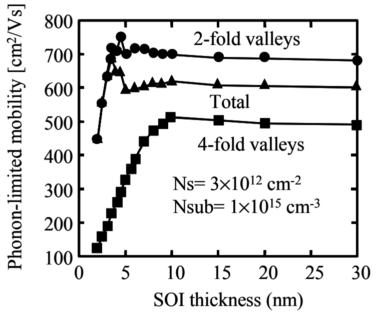

Fig. 7 Calculated electron μ_{phonon} in the 2-fold and the 4-fold valleys and the total electron μ_{phonon} as a function of T_{SOI}.

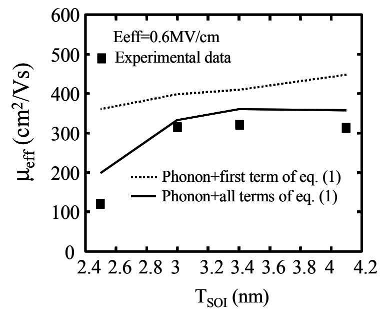

Fig. 8 Comparison of calculated inversion layer mobility in thin SOI films with the experimental one [3] as a function of T_{SOI} at E_{eff} of 0.6MV/cm.

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