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Quantitative Understanding of Mobility Degradation in High Effective Electric Field Region in MOSFETs with Ultra-thin Gate Oxides

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1. Introduction

It has been reported that the inversion layer mobility exhibits a significant reduction in gate oxides thinner than a critical thickness [1]. The reliable experimental results [2, 3] suggest that this mobility lowering can be associated with remote Coulomb scattering (RCS) due to impurities in poly-Si gate and enhanced roughness scattering. Although several theoretical works [4,5,6] have been made so far, the origin of mobility lowering in MOSFETs with ultra-thin gate oxides has not been fully understood yet.

In this study, we propose a new scattering mechanism “scattering due to sub-band energy fluctuation (SSEF)”, which can cause mobility lowering in MOSFETs with ultra-thin gate oxides. It is found that SSEF substantially causes enhanced roughness scattering, resulting in the significant mobility degradation without the increase of surface roughness in MOSFETs with ultra-thin gate oxides.

2. Proposal of new scattering mechanism

First, we explain the conventional model for surface roughness scattering. Surface roughness is characterized by the distortion of the interface position from the flat interface. We denote the distortion of the interface position as $\Delta_s(\mathbf{r})$ for the interface between substrate and gate oxide and $\Delta_r(\mathbf{r})$ for the interface between gate oxide and poly-Si gate. We also express the potential distribution in the substrate as $V_{sub}(z)$ and that in the poly-Si gate as $V_{poly}(z)$. The potential fluctuation in the substrate is expressed in the lowest order of $\Delta_s(\mathbf{r})$ as shown in Fig. 1, which is the conventional surface roughness scattering model [7]. Thus, the conventional model for surface roughness scattering is determined from the direct dependence of the potential fluctuation on the distortion of the interface.

On the other hand, it should be noted here that the distortion of the interface also causes the fluctuation of surface carrier concentration expressed as [8]:

$$\delta N_s(\mathbf{r})=N_s\delta T_{ox}(\mathbf{r})/T_{ox} \qquad (1)$$

where $\delta T_{ox}(\mathbf{r})= \Delta_s(\mathbf{r})-\Delta_r(\mathbf{r})$. The potential distribution in the poly-Si gate is expressed in the lowest order of $\Delta_r(\mathbf{r})$ and $\delta N_s(\mathbf{r})$ as shown in Fig. 1, which is the remote roughness scattering (RRS) model in ref. [9].

However, the fluctuations in the substrate due to $\delta N_s(\mathbf{r})$ have not been considered so far. It should be noted here that $\delta N_s(\mathbf{r})$ causes the fluctuation of the wave function in the inversion layer and of the potential distribution, as shown in Fig. 2. $\delta N_s(\mathbf{r})$ leads to the fluctuation of kinetic energy through the fluctuation of the wave function and potential energy through the fluctuation of the potential distribution as well as the fluctuation of the wave function (Fig. 2). By summing up these two fluctuations, we find the new fluctuation due to $\delta N_s(\mathbf{r})$, which can be expressed as the fluctuation of sub-band energy E_n:

$$\partial E_n/\partial N_s \cdot \delta N_s(\mathbf{r}) \qquad (2)$$

For convenience, we call the scattering component due to the fluctuation expressed by eq. (2) as “scattering due to sub-band energy fluctuation (SSEF)”. It should be noted that SSEF is caused by the indirect dependence of the kinetic and potential energy through N_s on the distortion of the interface position, in contrast with the conventional model for surface roughness scattering. Since $\delta N_s(\mathbf{r})$ becomes more significant with a decrease in gate oxide thickness, SSEF becomes more influential in MOSFETs with ultra-thin gate oxides. Therefore, we should add the SSEF effect to the conventional roughness scattering model for the quantitative understanding of the mobility lowering in MOSFETs with ultra-thin gate oxides.

3. Results

SSEF in MOSFETs with ultra-thin gate oxides is quantitatively examined. Calculation is performed by relaxation time approximation. For the quantitative examination, roughness parameters (correlation length and r.m.s value) need to be determined. We determine these values from the temperature dependence of the mobility limited by surface roughness scattering, μ_{RS}, for thick gate oxide (T_{ox}=20nm), where the RRS effect is negligible. For the evaluation of μ_{RS}, we assume roughness power spectrum in the form of Gaussian. Note that the temperature dependence of μ_{RS} is influenced by the value of correlation length, as shown in Fig. 3. The best fitting of the temperature dependence of universal curve provides Δ_s of 0.42nm and Λ_s of 0.7nm (Fig. 4). Fig. 5 shows the comparison of the calculated results of the mobility limited by RRS model in ref. [9] (μ_{RRS}) with that limited by SSEF (μ_{SSEF}). For the fair comparison, the same roughness parameters are used. It is found that SSEF lowers the mobility more significantly than RRS model in ref. [9]. Fig. 6 shows the behavior of the universal curve as a function of T_{ox}, which includes the effect of SSEF. Fig. 6 clearly shows the significant mobility degradation due to SSEF in MOSFETS with thinner gate oxides. Therefore, SSEF is considered to be the significant scattering mechanism that causes the mobility lowering with thinner gate oxides.

Based on this consideration, Fig. 7 shows the comparison of the experimental mobility lowering [3] with the calculated results of μ_{SSEF}. Note that the experimental mobility-lowering component was extracted using the Matthiessen’s rule [2,3]. It is found that the experimental result can be explained well without the increase of surface roughness by considering SSEF using the same roughness parameters between poly/gate-oxide interface and substrate/gate-oxide interface (Δ_s=Δ_r=0.42nm, Λ_s=Λ_r=0.7nm), which are reasonable values from a physical viewpoint. Fig. 8 also shows the comparison of the calculated T_{ox} dependence of the mobility lowering with the experimental one [2]. The agreement between the experiment and calculation indicates that the T_{ox} dependence of the mobility lowering in high E_{eff} region can be explained by 1/ T_{ox}^2 dependence (eq. (1)), in contrast with the conventional $exp(-qT_{ox})$ dependence in low E_{eff} region (q is the two dimensional wave number) [4]. When RRS model in ref. [9] is employed, on the other hand, *unphysical* large value of Δ_r =1nm with Λ_r=2.5nm is needed to represent the experimental results. Therefore, SSEF is one of the possible origins for enhanced roughness scattering in MOSFETs with thin gate oxides, though the increase in roughness at the early stage of oxidation process has been pointed out [3].

4. Conclusions

New scattering mechanism inherent to MOSFETs with ultra-thin gate oxides, “the scattering due to sub-band energy fluctuation (SSEF)”, has been proposed. It was found that SSEF substantially causes enhanced roughness, and, as a result, it leads to the significant mobility degradation without the increase of surface roughness in MOSFETs with ultra-thin gate oxides. It was also found that the experimental mobility lowering associated with thin gate oxides in high E_{eff} region can be explained well by considering SSEF. This fact indicates that SSEF becomes one of the dominant scattering mechanisms in MOSFETs with ultra-thin gate oxides.

References

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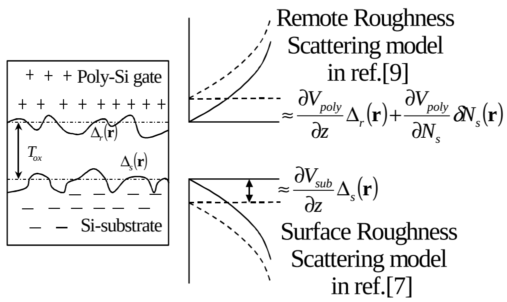

	r. m. s value	Correlation length
Substrate/gate-oxide interface	Δ_s	Λ_s
Poly-Si gate/gate-oxide interface	Δ_r	Λ_r

Fig. 1 Schematic diagram of conventional roughness scattering model.

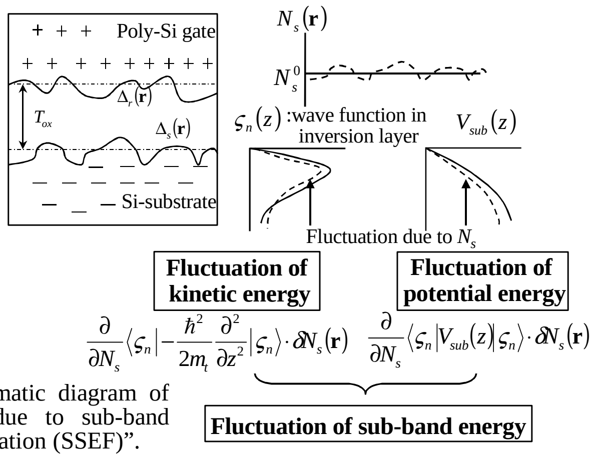

Fig. 2 Schematic diagram of “scattering due to sub-band energy fluctuation (SSEF)”.

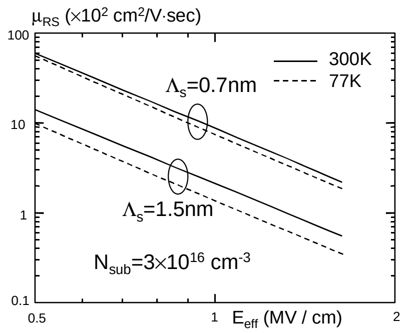

Fig. 3 Effective electric field (E_{eff}) dependence of μ_{RS} as parameters of temperature and roughness correlation length. Δ_s is taken to be 0.42nm.

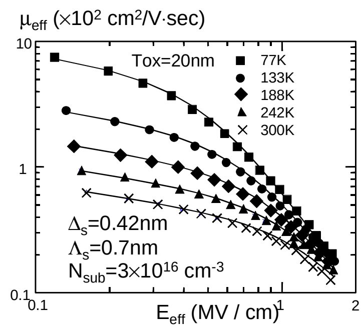

Fig. 4 E_{eff} dependence of universal curve as a parameter of temperature. Symbols and solid lines represent the experimental and simulated results, respectively.

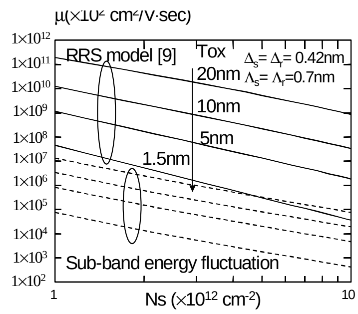

Fig. 5 Comparison of mobility limited by RRS model in ref. [9] with that limited by scattering due to sub-band energy fluctuation. $N_{sub}=3\times10^{16}$ cm^{-3}.

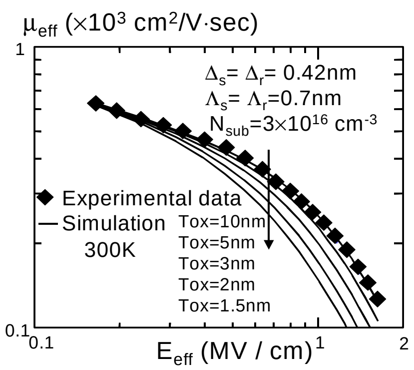

Fig. 6 E_{eff} dependence of universal curve as a parameter of T_{ox}.

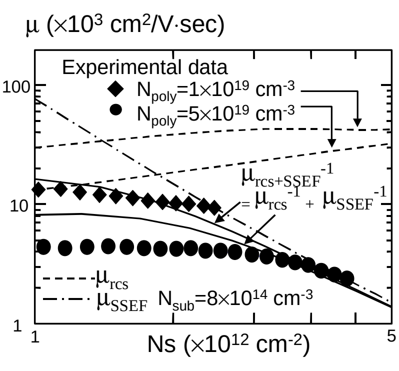

Fig. 7 Comparison of experimental mobility lowering [3] with calculated results. *Npoly* is donor concentration in the poly-Si gate. The calculated results of the mobility limited by RCS, μ_{RCS}, are also shown.

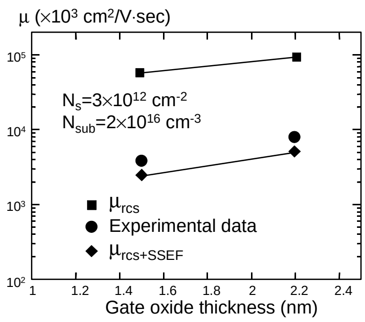

Fig. 8 Comparison of experimental mobility-lowering component [2] with μ_{RCS} and $\mu_{RCS+SSEF}$ as a function of T_{ox} at N_s of 3×10^{12} cm^{-2}.