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Physical Origins of Surface Carrier Density Dependences of Interface- and Remote-Coulomb Scattering Mobility in Si MOS Inversion Layer

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1. Introduction

Influence of Coulomb scattering ($\mu_{Coulomb}$) on the surface carriers in Si MOS inversion layer becomes a serious concern with CMOS scaling; heavily doped substrate and ultrathin gate insulator enhance impurity scattering (μ_{sub}) and remote Coulomb scattering (RCS, μ_{RCS}), respectively, whereas an introduction of novel gate stack material can induce interface charges which cause interface Coulomb scattering (μ_{it}). Although different behaviors of the surface carrier density (N_S) dependences were reported among μ_{sub}, μ_{it} and μ_{RCS} [1-4], physical origins of different N_S dependences have not been fully understood yet.

In this paper, we thoroughly examine the substrate bias (V_{sub}) dependence of each Coulomb scattering mobility, in order to clarify the physical origins of N_S and temperature dependences of Coulomb scattering mobility.

2. Experimental

The modified split CV method [2] in combination with the Takagi's method [3] was employed to measure an effective mobility (μ_{eff}) in MOS inversion layer (Fig. 1). All samples were conventional n-MOSFETs with an n^+ poly-Si gate. Coulomb scattering mobility components were extracted using the Matthiessen's rule, as shown in Fig. 2.

3. Results and Discussions

Fig. 3 shows the strongest N_S dependence of μ_{sub} and the weakest N_S dependence of μ_{RCS}. These results are similar to the previous works. It is widely accepted that the N_S dependence of μ_{sub} results from the screening effect [1]. Fig. 4 shows, on the other hand, that μ_{RCS} has the strongest dependence on the temperature. In the following sections, we discuss the physical origins, which is summarized in Fig. 5.

3.1. Physical Origin of N_S dependence of μ_{it}

Figs. 3 and 4 show that μ_{it} has weaker N_S and stronger temperature dependences than μ_{sub}. These behaviors can be explained in terms of the "position effect", which means that the distribution of the surface carriers shifts toward the Si/SiO_2 interface with increasing N_S or decreasing the temperature (Fig. 6). Since the interface states are localized at the Si/SiO_2 interface, the scattering probability increases when the relative distance between the surface carriers and the interface states become small. As a result, the position effect becomes significant with increasing N_S or decreasing the temperature (Fig. 5). This is why μ_{it} has weaker N_S and stronger temperature dependences than μ_{sub}.

In order to quantitatively examine the position effect, the mobility was measured under the finite V_{sub} conditions, because the distribution of the surface carriers can be controlled with the substrate biases. While the behavior of μ_{sub} is almost independent of V_{sub} (not shown), μ_{it} is gradually lowered with increasing $|V_{sub}|$ (Fig. 7). This is the direct experimental evidence of the position effect, because the increase in $|V_{sub}|$ leads to the shift of the surface carrier distribution toward the Si/SiO_2 interface. The obtained μ_{it} showed the linear relationship with $<Z_{AV}>$ (Fig. 8), where the average distance of inversion-layer electron from the interface $<Z_{AV}>$ corresponding to each V_{sub} was obtained from the self-consistent calculation [5]. This is the experimental evidence that the relaxation time is inversely proportional to $<Z_{AV}>$, though similar assumption was used in the previous model [6]. In summary, the obtained N_S dependence of μ_{it} results from the position effect in addition to the screening effect.

3.2. Physical Origin of N_S dependence of μ_{RCS}

RCS is mainly caused by the ionized impurities in the depletion layer of poly-Si gate [4]. According to the Gauss's law, the gate depletion charge density (N_{gate}) is equal to N_S+N_{dep}, where N_{dep} is the depletion charge density in the channel [7]. This fact indicates that the number of scattering centers that contribute to RCS increases with increasing N_S, or the gate voltage V_g (Fig. 9). The obtained N_S dependence of μ_{RCS} can be explained, considering this "number effect" as well as the position effect (Fig. 5).

In order to experimentally examine the number effect, V_{sub} dependence of μ_{RCS} was also measured. Fig. 10 shows that the N_S dependence becomes stronger with increasing $|V_{sub}|$. In the limit of high $|V_{sub}|$, N_{gate} is dominantly determined by N_{dep}, which results in the stronger N_S dependence (Fig .11(b)). On the other hand, since the substrate concentration is as low as $9x10^{14}cm^{-3}$, the number effect can not be ignored at V_{sub}=0V, which leads to the weaker N_S dependence because of the gradual change in the number of scattering centers (Fig. 11(a)).

4. Conclusions

Two physical origins are important to understand the N_S dependences of μ_{it} and μ_{RCS}. The position effect associated with the change in the surface carrier distribution leads to weaker N_S dependences in both cases. The number effect associated with the change in the number of scattering centers leads to the weakest N_S dependence of μ_{RCS}. Our new findings will contribute to an accurate modeling of Coulomb scattering mobility.

References

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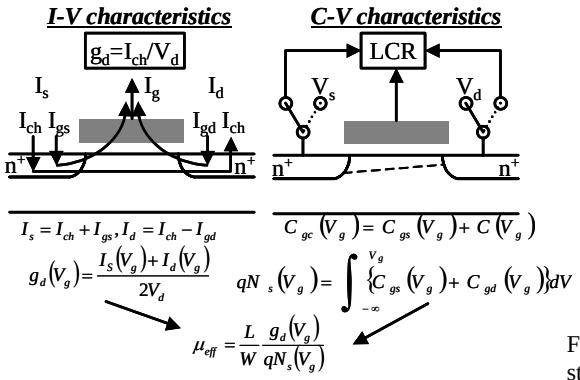

Fig.1 Mobility measurement method.

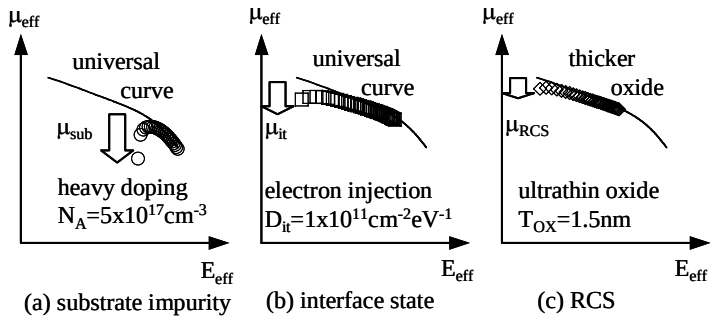

Fig. 2 Extraction method of $\mu_{Coulomb}$ for respective scattering centers. Interface states were generated by FN injection [1].

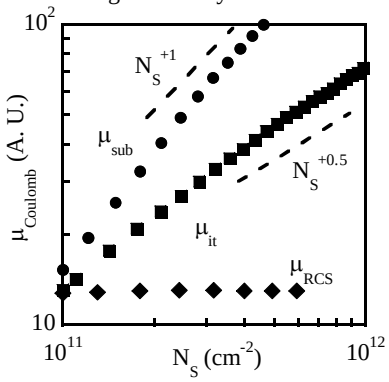

Fig. 3 N_S dependence of $\mu_{Coulomb}$ for respective scattering centers.

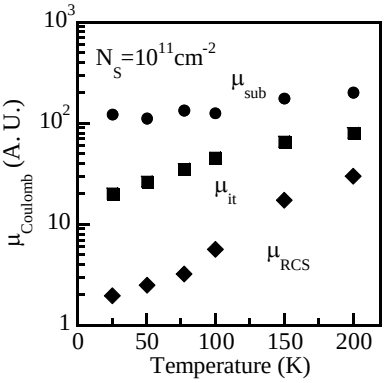

Fig. 4 Temperature dependence of $\mu_{Coulomb}$ for respective scattering centers.

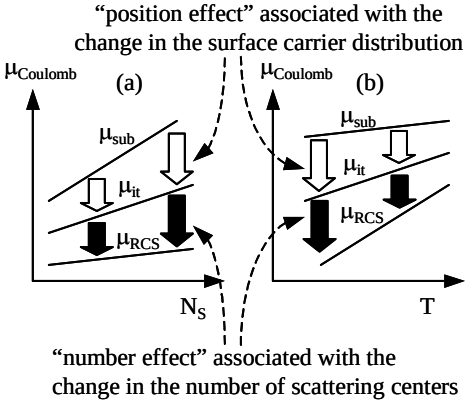

Fig. 5 Schematic diagram showing different (a) N_S and (b) temperature dependences for each Coulomb scattering mobility.

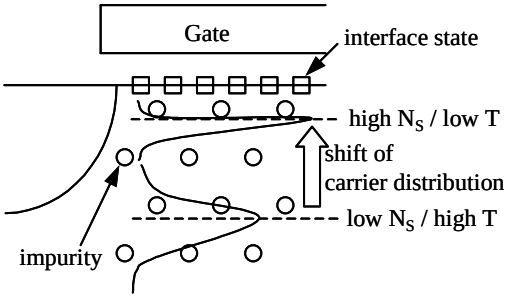

Fig. 6 Schematic diagram showing position effect. The distribution of the surface carriers shifts toward the Si/SiO_2 interface with increasing N_S or decreasing the temperature.

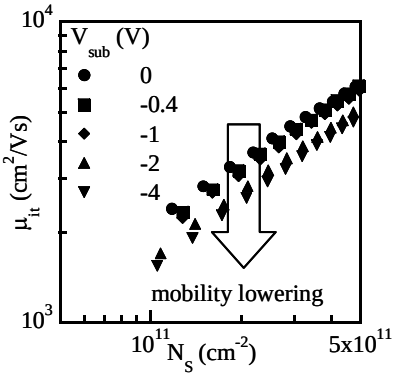

Fig. 7 N_S dependence of μ_{it} as function of V_{sub}. μ_{it} is gradually lowered with increasing $|V_{sub}|$.

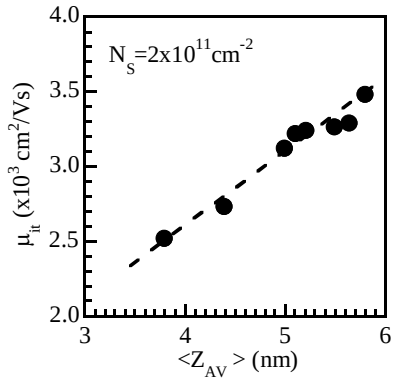

Fig. 8 Relationship between μ_{it} and $<Z_{AV}>$. $<Z_{AV}>$ corresponding to each V_{sub} was obtained from the self-consistent calculation.

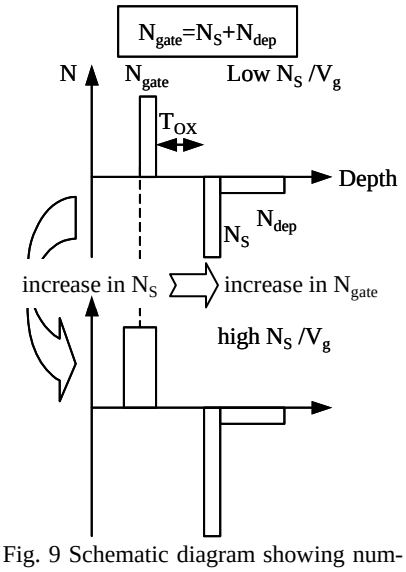

Fig. 9 Schematic diagram showing number effect. The number of scattering centers that contribute to RCS increases with increasing N_S, or V_g.

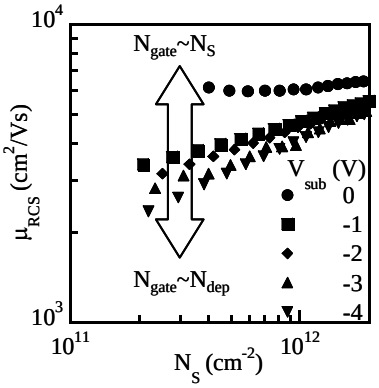

Fig.10 N_S dependence of μ_{RCS} as function of V_{sub}. The N_S dependence becomes stronger with increasing $|V_{sub}|$.

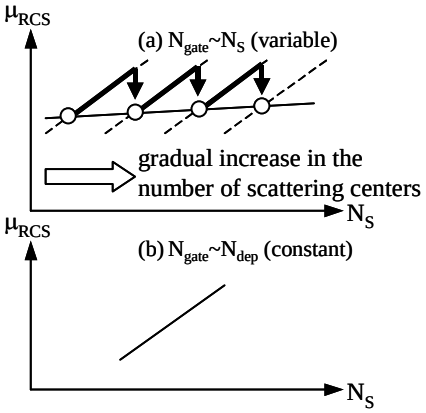

Fig.11 Schematic diagram showing physical origin of N_S dependence of μ_{RCS}.