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Influences of Gate-Poly Impurity Concentration on Inversion-Layer Mobility in MOSFETs with Ultrathin Gate Oxide Film

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Introduction

It has been reported that gate oxides thinner than a critical thickness deteriorates the drive current capability [1], strongly suggesting the reduction in inversion-layer mobility. Several scattering mechanisms inherent to ultrathin gate oxides, such as remote Coulomb scattering (RCS) [2,3], have been reported. However, because of the lack of reliable experimental data, the direct evidence of mobility lowering associated with these scattering mechanisms has not been obtained yet. Recently, Takagi and Takayanagi have proposed a modified mobility measurement method, which is applicable to MOSFETs with high gate leakage current [4]. In this paper, we experimentally examine the influences of poly-Si-gate impurity concentration (N_{poly}) on inversion-layer mobility (μ_{eff}) in MOSFETs with ultrathin gate oxides (T_{ox}) in order to make clear whether or not RCS due to the gate impurities affects μ_{eff}. It is found that the mobility is significantly reduced for highly doped gate at T_{ox} of 1.5 nm or less, strongly suggesting the contribution of RCS due to the gate impurities, *which is quantitatively discriminated from that of Coulomb scattering due to substrate impurities and interface states*.

Measurement and Device Fabrication

The split *CV* method was modified to measure an effective mobility in the MOS inversion layer. The keys are (i) to accurately determine conductance and capacitance ever under high gate leakage current and (ii) to evaluate correct surface carrier density (N_s) even at a finite drain bias (V_d). Since a finite value of V_d causes the decrease in N_s near the drain region, the mobility evaluation without any considerations on it has a serious error, particularly in a low field (E_{eff}) region [5], in which a mobility lowering occurs as shown later. In this work, Takagi's method [4] was employed in combination with the gate-source and gate-drain capacitance method [5] (Fig.1).

The samples were conventional *n*-MOSFETs with an n^+ poly-Si gate. The substrate impurity concentration was left undoped, 9×10^{14} cm^{-3}, to minimize the contribution of Coulomb scattering due to substrate impurities. The gate oxides ranging from 1.5 nm to 5.7 nm were pure SiO_2 film formed by rapid thermal oxidation (RTO). MOSFETs with two N_{poly} values of 1×10^{19} cm^{-3} and 6×10^{19} cm^{-3} were prepared by changing arsenic implantation dose. SIMS analysis confirmed that there is no impurity penetration from the poly-Si gate into the Si substrate (Fig.2).

Results and Discussions

Fig.3 shows the μ_{eff} -E_{eff} curve for nMOSFETs with N_{poly} of 6×10^{19} cm^{-3}. The μ_{eff} behaviors are identical for T_{ox} greater than 1.9 nm, though the slight μ_{eff} lowering from the universal μ_{eff} curve is seen even at T_{ox} of 5.7 nm. This is attributed to Coulomb scattering due to the charges at the channel/oxide interface. Interface state density (D_{it}) of 7-8$\times10^{10}$ cm^{-2}eV^{-1}, evaluated by the charge pumping method, quantitatively agrees with the μ_{eff} lowering ($\mu_{coulomb}$) at T_{ox} larger than 1.9 nm (Fig.4). The observed higher D_{it} results from the RTO process.

In MOSFETs with T_{ox} of 1.5 nm, on the other hand, further μ_{eff} lowering is clearly seen, particularly in the low E_{eff} region. In order to confirm whether this μ_{eff} lowering is related to the gate impurities, the mobility for different N_{poly} of 1×10^{19} cm^{-3} was examined. As shown in Fig.5, the μ_{eff} lowering is smaller at T_{ox} of 1.5 nm than that with the higher N_{poly} (Fig.3). Since other extrinsic factors affecting mobility are the same between the two different values of N_{poly}, it is concluded that the observed μ_{eff} lowering inherent to ultrathin gate oxides becomes more significant with an increase in N_{poly}.

The mobility-lowering component inherent to ultrathin T_{ox}, $\mu_{lowering}$, was extracted using the Matthiessen's rule. Fig.6 shows the $\mu_{lowering}$-N_s curve as a function of N_{poly}. It is noted that $\mu_{lowering}$ at low N_s is strongly dependent on N_{poly}. This agrees with the theoretical calculations of RCS (solid lines) including screening effect from free carriers in gate electrode [6], suggesting that the present $\mu_{lowering}$ associated with ultrathin T_{ox} is explainable by the framework of RCS. In the higher N_s region, $\mu_{lowering}$ is also affected by roughness scattering, resulting in the decrease in $\mu_{lowering}$ with the increase in N_s at N_{poly} of 1×10^{19} cm^{-3}. The experimental results at a low temperature strongly suggest that the mobility limited by roughness scattering is degraded at T_{ox} of 1.5 nm (Fig.7).

Conclusion

The mobility lowering associated with the gate impurities has been quantitatively evaluated by discriminating the contribution of Coulomb scattering due to substrate impurities and interface states from the total mobility. It was found that the mobility in ultrathin gate oxides lowers significantly for highly doped gate at T_{ox} of 1.5 nm or less. The present mobility lowering inherent to ultrathin T_{ox} is explainable by the framework of remote Coulomb scattering, in addition to enhanced roughness scattering.

Acknowledgment

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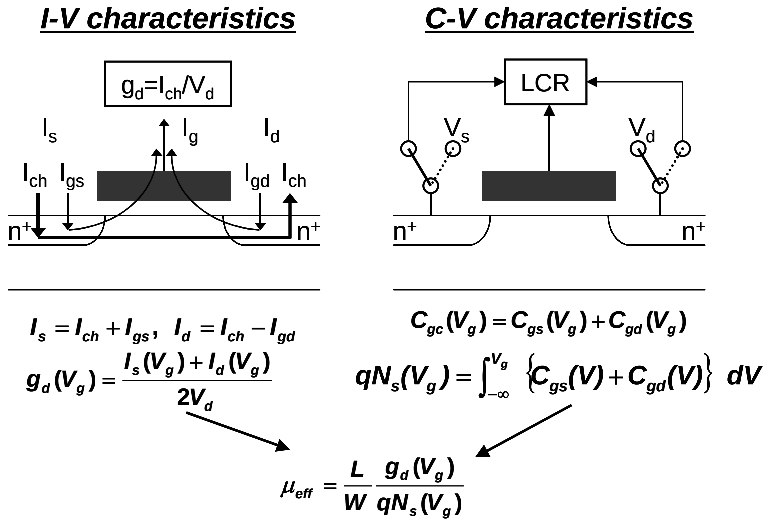

Fig.1: Mobility measurement method. N_s can be determined directly through the *CV* measurements. It should be noted that the poly-Si-gate depletion effects are correctly incorporated through the *CV* measurements.

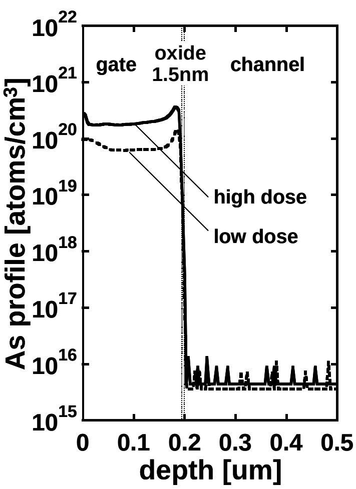

Fig.2: SIMS profile. There is no impurity penetration from the poly-Si gate into the Si substrate.

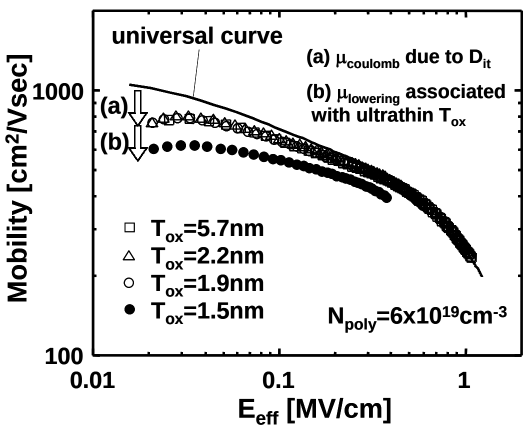

Fig.3: Dependence of μ_{eff} on E_{eff} for MOSFETs with N_{poly} of 6×10^{19} cm^{-3}. Solid line stands for the universal mobility curve.

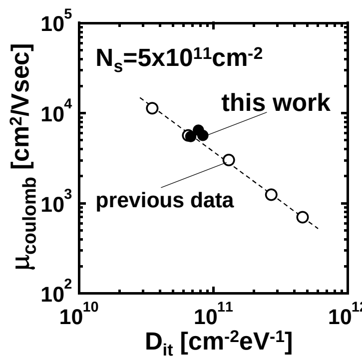

Fig.4: Mobility lowering component limited by Coulomb scattering due to interface states. Open circles stand for the previous data [5] obtained by generating the interface states through FN injection.

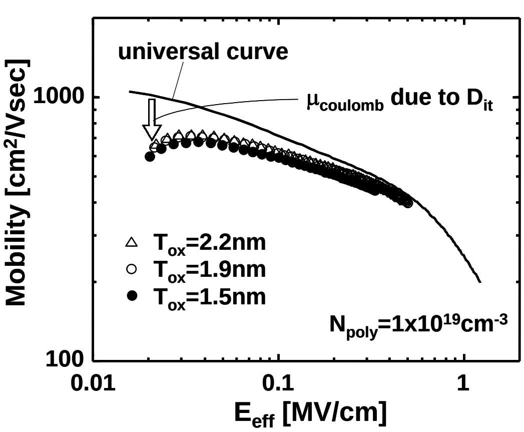

Fig.5: Dependence of μ_{eff} on E_{eff} for MOSFETs with N_{poly} of 1×10^{19} cm^{-3}. Poly gate doping strongly affects μ_{eff} at T_{ox} of 1.5 nm.

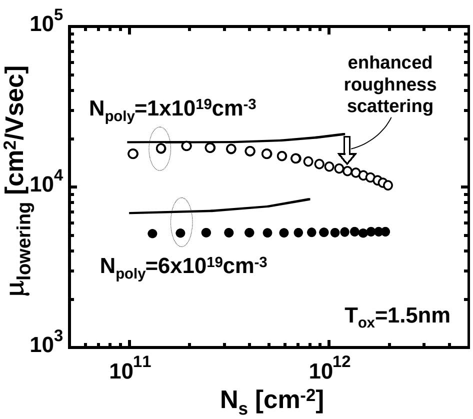

Fig.6: Extracted $\mu_{lowering}$-N_s curve as function of N_{poly}. Solid lines stand for the theoretical calculations [6]. $\mu_{lowering}$ can be explained by the combination of RCS and enhanced roughness scattering.

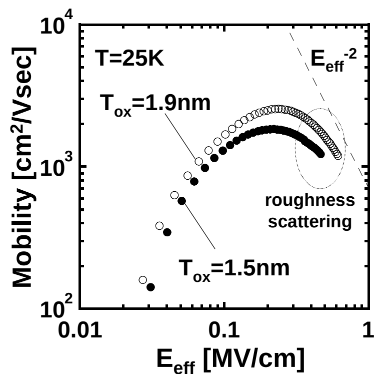

Fig.7: Dependence of μ_{eff} on E_{eff} for MOSFETs at 25 K. The mobility limited by roughness scattering in the high E_{eff} region is degraded at T_{ox} of 1.5 nm.