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Mobility Reduction due to Remote Charge Scattering in Al_2O_3/SiO_2 Gate-Stacked MISFETs

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1. Introduction

High-permittivity gate dielectrics (high-κ) are promising materials for low stand-by power devices at sub-100-nm technology nodes. However, the effective mobility ($\mu_{\rm eff}$) of high-κ MISFETs is limited to much smaller than the universal one. In our previous paper on Al_2O_3/SiO_2 MISFETs [1], we developed a calculation method to explain such a mobility reduction in terms of remote charge scattering (RCS) that is induced by fixed charge.

Recently, it has turned out that $\mu_{\rm eff}$ decreases even further with reducing the thickness of interfacial oxide ($t_{\rm int}$) between the gate dielectrics and Si substrate [2]. In this paper, we extend our calculation method to explain the dependence of $\mu_{\rm eff}$ on $t_{\rm int}$.

2. Theory

Our fixed-charge model assumes that there are two types of fixed charges, as shown in Fig. 1 [1]: one is located at the poly-Si/Al_2O_3 interface, and it induces a flat-band voltage shift ($\Delta V_{\rm FB}$) in a capacitance-voltage measurement; and the other is at the Al_2O_3/SiO_2 interface, and it is responsible for the mobility reduction, however, it does not contribute to $\Delta V_{\rm FB}$. This is reasonable, because our model assumes that the fixed charges with both negative and positive signs are trapped at the Al_2O_3/SiO_2 interface, and consequently that the net charges are canceled to be negligibly small.

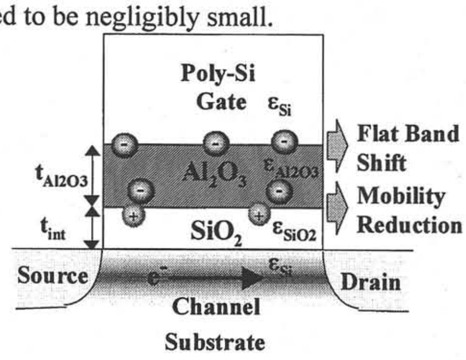

Fig. 1 Al_2O_3/SiO_2 gate-stacked MISFET. Two types of fixed charges are assumed to explain $\Delta V_{\rm FB}$ and reduced $\mu_{\rm eff}$.

Our calculation procedure is based on a classical linear response theory [3]. We calculated the scattering potential ($\bar{A}_{\rm q}$) that is induced by the fixed charge (Ze) located at the Al_2O_3/SiO_2 interface using a Green's function method. We first introduced a dielectric constant ($\varepsilon_{\rm Al2O3}$, $\varepsilon_{\rm SiO2}$, $\varepsilon_{\rm Si}$) for each of the Al_2O_3, SiO_2, and Si layers, and obtained an image charge resulted from the difference (β_i, i=1-3). Second, we took into account the effect of the finite oxide thickness ($e^{-2qt_{\rm Al2O3}}$) on the potential. Third, the quantum mechanical effect ($P_{\rm av}$, P_0) that keeps an inversion layer away from the substrate interface was taken into account. As a result, the Fourier-Bessel transform of the potential is given by

$$\bar{A}_q = \frac{(1-\beta_1)(1-\beta_2)Ze}{4\pi\varepsilon_{\rm Al2O3}}\gamma_0 P_0 e^{-3qt_{\rm int}} \frac{1+\beta_3 e^{-2qt_{\rm Al2O3}}}{q+q_{\rm s}(q)(P_{\rm av}+\gamma_1 P_0^2)} \quad , (1)$$

where we defined that

$$\gamma_0 = \left(\beta_2\beta_3 e^{-2q(t_{\rm int}+t_{\rm Al2O3})} + e^{-2qt_{\rm int}}(1+\beta_1(\beta_2 e^{-2qt_{\rm int}} + \beta_3 e^{-2q(t_{\rm int}+t_{\rm Al2O3})}))\right)^{-1} \quad , (2)$$

$$\gamma_1 = \gamma_0(\beta_1\beta_2\beta_3 e^{-2q(t_{\rm int}+t_{\rm Al2O3})} + e^{-2qt_{\rm int}}(\beta_1 + \beta_2 e^{-2qt_{\rm int}} + \beta_3 e^{-2q(t_{\rm int}+t_{\rm Al2O3})})) \quad , (3)$$

$$\beta_1 = (\varepsilon_{\rm Si} - \varepsilon_{\rm SiO2})/(\varepsilon_{\rm Si} + \varepsilon_{\rm SiO2}) \quad , (4)$$

$$\beta_2 = (\varepsilon_{\rm SiO2} - \varepsilon_{\rm Al2O3})/(\varepsilon_{\rm SiO2} + \varepsilon_{\rm Al2O3}) \quad , (5) \text{ and}$$

$$\beta_3 = (\varepsilon_{\rm Al2O3} - \varepsilon_{\rm Si})/(\varepsilon_{\rm Al2O3} + \varepsilon_{\rm Si}) \quad . (6)$$

The other parameters were the same as those defined in Ref. [3].

The RCS-limited mobility ($\mu_{\rm RCS}$) was calculated on the assumption that a fixed charge with a density of $N_{\rm fix}$ is located at the Al_2O_3/SiO_2 interface. Here, $\mu_{\rm RCS}$ is inversely proportional to $N_{\rm fix}$. In general, the universal mobility ($\mu_{\rm univ}$) was determined by the scattering from phonons and surface roughness [4]. Thus, we added the contributions of $\mu_{\rm RCS}$ and conventional Coulomb scattering ($\mu_{\rm Coulomb}$) from interface traps and substrate impurities to the universal mobility according to Matthiessen's rule

$$\frac{1}{\mu_{\rm eff}} = \frac{1}{\mu_{\rm univ}} + \frac{1}{\mu_{\rm Coulomb}} + \frac{1}{\mu_{\rm RCS}} \quad . (7)$$

3. Device Fabrication

We fabricated an Al_2O_3/SiO_2 MISFET with an Al_2O_3 layer thickness ($t_{\rm Al2O3}$) of 2.0 nm by a gate-last process [1]. An interfacial SiO_2 layer with $t_{\rm int}$ of 0.9 to 2.0 nm was grown by oxidation prior to Al_2O_3 deposition. The Al_2O_3 dielectric was deposited by ALCVD.

4. Results and Discussions

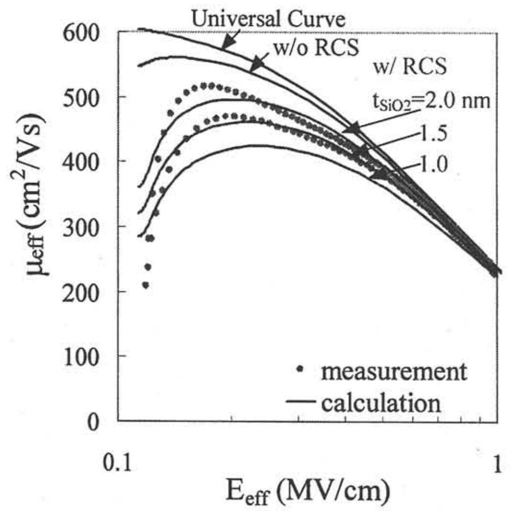

Fig. 2 Calculated mobilities agree well with measured ones for SiO_2 gate dielectric irrespective of the thickness (t_{SiO2}).

We first applied the calculation to a simple SiO_2 gate dielectric, where the remote charge with an amount of 1×10^{12}-1×10^{13} cm^{-2} has been identified as a depleted charge in poly-Si gates, and it increases with an effective field (E_{eff}) [5, 6]. The calculated μ_{eff} was in good agreement with the experimental results without introducing additional refinement parameters (Fig. 2), which indicates that the calculation procedure is correct.

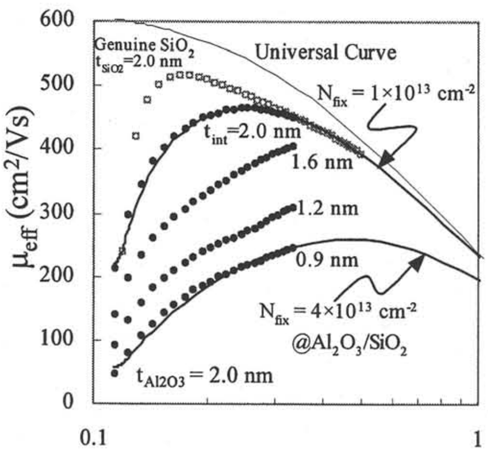

Fig. 3 Calculated (lines) and experimental (dots) μ_{eff} that are improved with increasing t_{int}.

Figure 3 shows the dependence of μ_{eff} on E_{eff} for the Al_2O_3/SiO_2 gate stacks with different SiO_2 thickness (t_{int}). The measured μ_{eff} (dots) improved with increasing t_{int}. This was anticipated in our model in which the fixed charge at the Al_2O_3/SiO_2 interface gets away from the inversion layer with increasing t_{int}. Thus, the RCS potential decreases, *i.e.*, μ_{RCS} increases. The measured data were well simulated by the present model with only one refinement parameter, namely, the fixed charge density (N_{fix}) at the Al_2O_3/SiO_2 interface. In particular, note that the mobility at t_{int}=2.0 nm was comparable to that at the simple SiO_2 dielectric (2.0 nm) at high E_{eff}. This strongly suggests that the fixed charge with a quantity of an order of 10^{13} cm^{-2} exists at the Al_2O_3/SiO_2 interface, similar to the simple SiO_2 dielectric. The calculated and experimental results are compared in Fig. 4, where μ_{eff} is plotted against t_{int} (including the data from Ref. [1, 7, 8]). The improvement in μ_{eff} is explained by the increase in t_{int} and the decrease in N_{fix} from 4×10^{13} to 1×10^{13} cm^{-2} with increasing t_{int}.

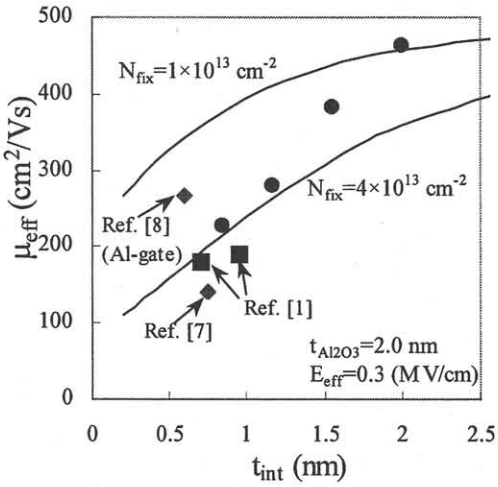

Fig. 4 Dependence of effective mobility on interfacial oxide thickness both in calculations (lines) and in experiments (dots).

In various high-κ MISFETs, the mobility typically improves with increasing t_{int} [2]. Therefore, obtaining the high-quality interfacial layer is the key to improving the mobility of MISFETs, while the interfacial thickness is suppressed to approximately 0.5 nm.

5. Conclusions

We found that the effective mobility of Al_2O_3/SiO_2 MISFETs increases with increasing the interfacial SiO_2 layer thickness. This can be explained by remote charge scattering due to the fixed charge at the Al_2O_3/SiO_2 interface. A process for fabricating high-quality 0.5-nm-thick interfacial SiO_2 layers is needed for high-κ gate stacks.

References

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