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Projection of Mobility Degradation in $HfAlO_x$ / SiO_2 nMOSFET towards the Reduction of Interfacial Oxide Thickness

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1. Introduction

Low mobility in high-k dielectric MOSFET is one of the major concerns toward its implementation into CMOS circuit. Understanding of carrier scattering mechanism and the mobility degradation with the reduction of interfacial layer thickness (T_{int}) will provide a physical basis for improving mobility in high-k MOSFET. Recent studies on the mobility of Al_2O_3 MOSFETs [1,2] indicate that the dominant carrier scattering mechanism is remote charge scattering (RCS), and that the mobility degradation with the reduction of T_{int} can also be explained by RCS.

We study the mobility degradation of $HfAlO_x/SiO_2$ nMOSFET, where another scattering mechanism might also contribute due to the presence of HfO_2 [3]. In this paper we show that scattering rate originating from $HfAlO_x/SiO_2$ films increases exponentially with the decrease of T_{int}, and its scaling length is characterized by Fermi (or thermal) wave length of channel carriers. We also show that the mobility degradation contains non-Coulomb scattering, in addition to RCS.

2. Experimental

Thin SiO_2 layers (T_{int} =1.5, 2.0, and 3.0 nm) were first grown on 1Ωcm p-Si(100) substrates at 950°C in 1% O_2. Then, $HfAlO_x$ films were deposited with LL-D&A [4]. About 0.8nm-thick $HfAlO_x$ film (Hf: 60at.%) was deposited, and subsequent *in-situ* RTA was performed at 650°C in O_2 at 130Pa. This sequence was repeated to obtain 4nm-thick $HfAlO_x$. Poly-Si gate nMOSFETs were fabricated using a conventional process with activation anneal in N_2 at 950°C for 20s. I_d-V_g and C_{gc}-V_g (f=1kHz) were measured on W/L=190/500μm FETs, and μ–N_s (N_s: surface carrier density) or E_{eff} characteristics were evaluated from the split C-V method.

3. Results and Discussion

Figure 1 shows the experimental mobility of $HfAlO_x/SiO_2$ (T_{int}=1.5, 2.0, 3.0nm) nMOSFETs and the universal mobility. In order to study the mobility degradation in Fig. 1, the mobility due to scatterings from the $HfAlO_x/SiO_2$ film, μ_{dielec}, was evaluated as $1/\mu_{dielec} = 1/\mu_{meas} - 1/\mu_{univ}$ where μ_{meas} and μ_{univ} are the measured and the universal mobility, respectively. A theoretical calculation of RCS based on Stern-Howard model [5] was also performed, which includes a scattering potential with proper boundary conditions of the gate stack [6]. From the experimental and calculated results in Fig. 2, we can assume that RCS is the major scattering in a lower N_s region, while another scattering mechanism of the $HfAlO_x/SiO_2$ film is predominant in a higher N_s region.

Figures 3 and 4 show the scaling of the scattering rate from the gate dielectrics ($\propto 1/\mu_{dielec}$), with the reduction of T_{int}. The characteristic scaling length λ was evaluated as $1/\mu_{dielec} \propto \exp(-T_{int}/\lambda) \propto \exp(-CET/\lambda)$, as shown in Fig. 3, and the dependence of λ on N_s is plotted in Fig. 4. It is found that λ at high N_s (i.e. degenerate N_s) is described as $\lambda=1/(2k_F)\approx 1/\{2(\pi N_s)^{1/2}\}$, while λ is a constant and around the thermal wave length at low N_s. As shown in Fig. 5, the physics behind it is as follows: The scattering potential from the $HfAlO_x/SiO_2$ interface has an exponential dependence expressed as exp(-Qz), where Q is two-dimensional wave number and z is distance, and channel carriers with Fermi wave length (or thermal wave length at low N_s) are responsible for electrical conduction and scattering. Note that this physical model was pointed out for remote phonon scattering (RPS) in Ref.[3]. We infer, however, that our experimental result is not necessarily a direct evidence for RPS, because the exponential dependence of a scattering potential on T_{int} is due to the boundary condition of Maxwell equation [3,6], and thus a similar dependence is also expected for other scatterings originating from the $HfAlO_x/SiO_2$ interface.

From the experimental results and RCS simulation, we can predict the "ideal" mobility of $HfAlO_x/SiO_2$ nMOSFET when RCS is completely eliminated. The ideal mobility, μ_{ideal}, was defined as $1/\mu_{ideal}=(1/\mu_{dielec}-1/\mu_{RCS})+1/\mu_{univ}$. In Fig. 6 we show the projection of μ_{ideal} to various T_{int}, using the scaling rule of $1/\mu_{dielec} \propto \exp\{-T_{int}/\lambda(N_s)\}$ (the same dependence also assumed for $1/\mu_{RCS}$), and the μ_{ideal}-N_s relation at T_{int}=1.5nm as a reference. The degradation of μ_{ideal} is predicted to be very severe with the reduction of T_{int}, particularly at high N_s. Note that this projection corresponds to the best mobility in the conventional fabrication technology, and it is not clear at the moment whether or not the projected mobility is intrinsic to the $HfAlO_x/SiO_2$ system.

4. Conclusions

The scattering rate from $HfAlO_x/SiO_2$ films increases exponentially with the decrease of T_{int}, and its characteristic scaling length is described with Fermi wave length at high N_s (and thermal wave length at low N_s). The scattering from the gate dielectrics includes non-Coulomb component, in addition to RCS. Based on these results, there is a concern that the mobility of $HfAlO_x$ nMOSFET degrades with the reduction of T_{int}, particularly at high N_s, even if RCS is completely eliminated.

Acknowledgments

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References

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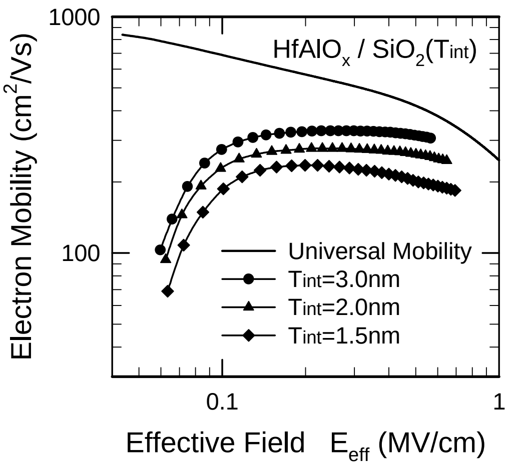

Fig. 1 Electron mobility of $HfAlO_x/SiO_2$ nMOSFET as a function of E_{eff}, for T_{int}=1.5, 2.0 and 3.0 nm. Solid curve shows the universal mobility.

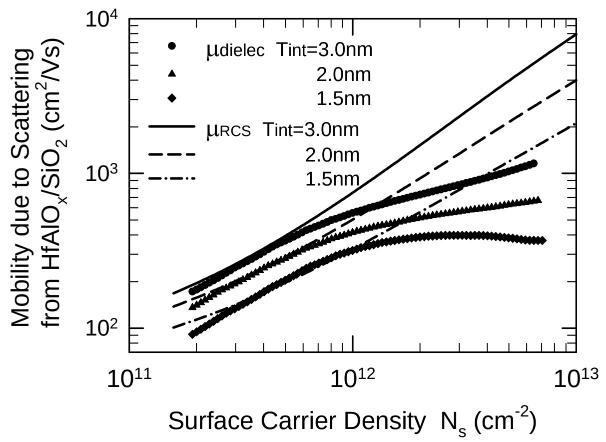

Fig. 2 Mobility due to scattering from $HfAlO_x/SiO_2$ films, as a function of N_s (surface carrier density). Symbols: experimentally derived mobility (μ_{dielec}). Lines: theoretical calculation of RCS (μ_{RCS}). Fixed charges were assumed to be located around one monolayer of the $HfAlO_x/SiO_2$ interface region.

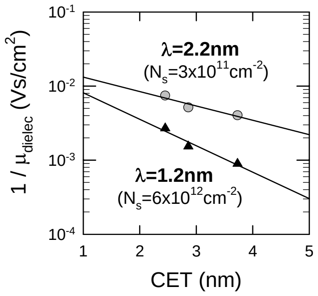

Fig. 3 $1/\mu_{dielec}$ (a quantity proportional to the scattering rate from the gate dielectrics) as a function of CET (capacitance equivalent thickness). $1/\mu_{dielec}$ shows an exponential dependence on CET (thus on T_{int}).

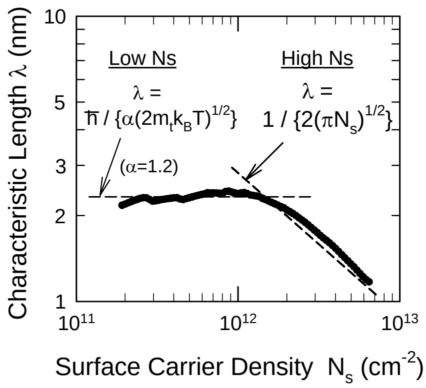

Fig. 4 Characteristic scaling length λ as a function of N_s.

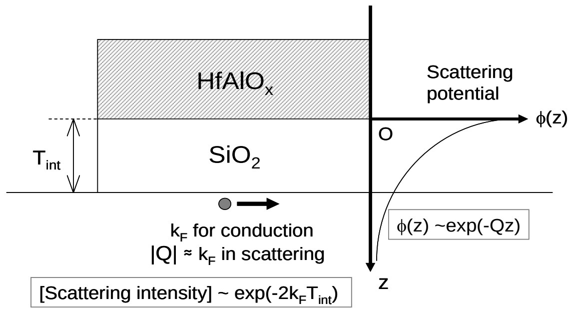

Fig. 5 Physical model for the dependence of scattering rate on interfacial oxide thickness. Channel carriers with Fermi wave length are responsible for scattering.

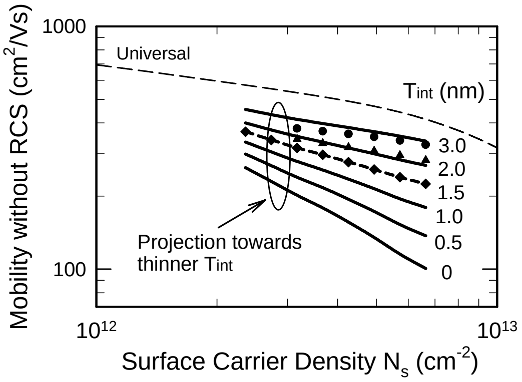

Fig. 6 Ideal mobility without RCS, μ_{ideal}. Symbols: $1/\mu_{ideal}=(1/\mu_{dielec}-1/\mu_{RCS})+1/\mu_{univ}$ from Fig. 2. Solid lines: projection of μ_{ideal} to various T_{int}, using $\lambda(N_s)$ in Fig. 4, and μ_{ideal} at T_{int}=1.5nm as a reference.