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Weak Temperature Dependence of Non-Coulomb Scattering Component of $HfAlO_x$-Limited Inversion Layer Mobility in n^+poly-Si/$HfAlO_x$/SiO_2 n-MOSFETs

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1. Introduction

Low mobility in high-k MOSFETs relative to the SiO_2 MOSFET is one of the major concerns for their application to CMOS circuits. Thus, there is much interest in the physical mechanisms of mobility degradation. Several theoretical mobility models peculiar to high-k MOSFETs have been proposed [1-4], and comparisons of theoretical and experimental results are also reported [5-7].

In this paper we report an analysis on the temperature dependence of $HfAlO_x$-limited mobility. We extract it from the degradation characteristics of measured mobility as a function of interfacial SiO_2 layer thickness. This approach is different from those of previous works [5,7], and an accurate evaluation of high-k dielectric-limited mobility can be expected. As a result of this work, non-Coulomb scattering is predominant in $HfAlO_x$-limited mobility. Its temperature dependence is weak, and is explainable by the scattering from low energy phonons.

2. Experimental

Thin SiO_2 layers (T_{int} =1.6, 2.6nm in TEM) were grown on 1Ωcm p-Si(100) substrates. Then, $HfAlO_x$ films (Hf: 60at.%) were deposited with a *layer-by-layer deposition and annealing* method [8]. N^+poly-Si gate n-channel MOSFETs were fabricated with a conventional gate-first process where the activation annealing was performed at 950℃. In the evaluation of mobility, the surface carrier density N_s was measured with the split C-V method.

3. Results and Discussion

Figure 1 shows a schematic illustration of remote scattering intensity. The measured mobility μ_m in the strong inversion can be expressed as [9]

$$\mathbf{1/\mu_m = (1/\mu_R)\exp(-2k_F T_{int}) + 1/\mu_{univ}} \qquad \mathbf{(1)}$$

where $\mathbf{k_F=(\pi N_s)^{0.5}}$ is the Fermi wavenumber in the strong inversion ($N_s > 8\pi m_t k_B T/h^2$), T_{int} is the thickness of an interfacial SiO_2 layer, and μ_{univ} is the universal mobility. From eq.(1), the slope of $1/\mu_m$ vs. $\exp(-2k_F T_{int})$ gives the pre-factor mobility of remote scattering μ_R. **Figure 2** shows a typical example of the measured mobility μ_m on n^+poly-Si/$HfAlO_x$/SiO_2(T_{int}) n-channel MOSFETs with T_{int} = 1.6 and 2.6 nm, in the temperature range of 77-297K. The inverse of the measured mobility $1/\mu_m$ was plotted against $\exp(-2k_F T_{int})$ as shown in **Fig. 3** for N_s=8x10^{12}cm^{-2}, where all the available mobility data on the sample wafers were indicated. Also note that the plots of $1/\mu_m$ at $\exp(-2k_F T_{int})$=0 are the universal mobility data by Takagi *et al*. [10]. Linear lines are obtained between $1/\mu_m$ and $\exp(-2k_F T_{int})$ for all the temperatures, demonstrating the validity of eq.(1). By performing this analysis for arbitrary N_s, the temperature dependence of the pre-factor mobility μ_R was extracted as a function of N_s, as shown in **Fig. 4**. The pre-factor mobility μ_R in a high N_s region decreases with temperature. This is an unambiguous evidence for the presence of non-Coulomb scattering component in $HfAlO_x$-limited mobility. However, Coulomb scattering component is present as well, as indicated by the increase of μ_R with N_s in a low N_s region. In order to discuss the mechanism of non-Coulomb scattering, it is necessary to separate the mobility components of Coulomb and Non-Coulomb scatterings. We performed a remote Coulomb scattering simulation [11], taking into account the exact boundary conditions for the gate stacks [12]. The density of fixed charges as shown in **Fig. 5** was used in this simulation, which was obtained from experimental results between the threshold voltage shift relative to SiO_2 MOSFET, and the physical thickness of $HfAlO_x$ [13]. The pre-factor mobility for remote Coulomb scattering (μ_{RC}) was evaluated from the calculated Coulomb mobility (μ_{mC}), using a formulation $1/\mu_{mC}=1/\mu_{RC}\exp(-2k_F T_{int})$, as shown in Fig. 5. By subtracting μ_{RC} from μ_R in Fig. 4, the pre-factor mobility for non-Coulomb scattering (μ_{RNC}) was extracted as $1/\mu_{RNC}=1/\mu_R-1/\mu_{RC}$, as shown in **Fig. 6**. The temperature dependence of μ_{RNC} at N_s = 8x10^{12}cm^{-2} was plotted in **Fig. 7**. For comparison, the mobility limited by surface-optical phonon μ_{phonon} was calculated as a function of TO phonon energy [14]. The weak temperature dependence of μ_{RNC} can quantitatively be explained by the scattering from low energy optical phonons. The TO phonon energy producing a similar temperature dependence to μ_{RNC} is <u>less than 20meV</u>. This result corresponds to the typical phonon energy for HfO_2-based materials as reported in Ref.[1].

4. Conclusions

We studied the temperature dependence of $HfAlO_x$ (Hf: 60at%)-limited mobility, using the exponential dependence of remote scattering intensity on interfacial SiO_2 thickness. Non-Coulomb scattering is predominant in a high N_s region. The non-Coulomb scattering mobility has a weak temperature dependence, and it is explainable by the scattering from low energy phonons (less than 20meV). This result suggests a possible contribution of low energy HfO_2 optical phonons to the mobility of $HfAlO_x$ n-MOSFETs. In order to improve the mobility, controls of phonon characteristics may be necessary.

Acknowledgments

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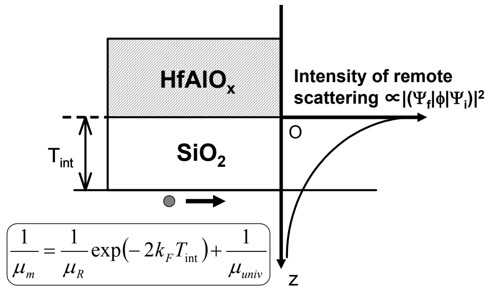

Fig. 1 Schematic illustration of remote scattering intensity, and an equation to describe the dependence of measured mobility μ_m on interfacial layer thickness T_{int}.

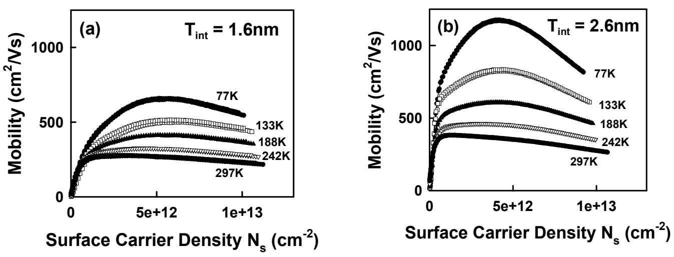

Fig. 2 Measured mobility on n^+poly-Si/$HfAlO_x$/SiO_2(T_{int}) n-channel MOSFETs with T_{int}=1.6, 2.6nm in 77 – 297K.

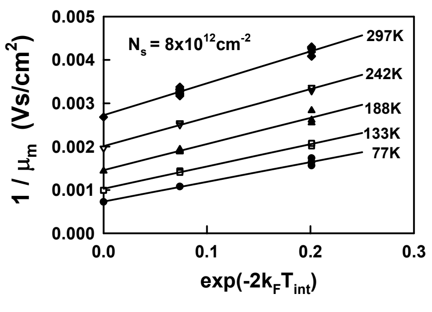

Fig. 3 Plots of $1/\mu_m$ vs. $\exp(-2k_FT_{int})$ at N_s=8x10^{12}cm^{-2} in 77-297K, with the universal curve at $\exp(-2k_FT_{int})$=0.

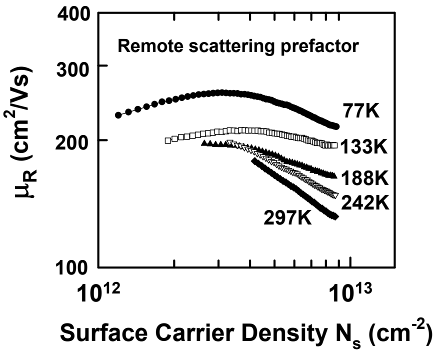

Fig. 4 Pre-factor mobility of $HfAlO_x$ μ_R as a function of N_s, with temperature as a parameter.

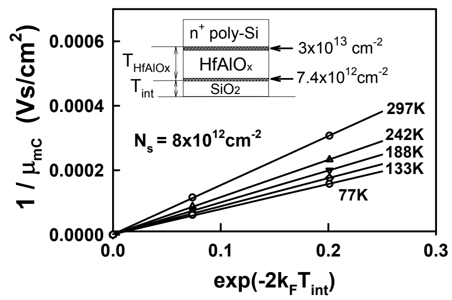

Fig. 5 Inverse of simulated remote Coulomb scattering mobility $1/\mu_{mC}$ vs. $\exp(-2k_FT_{int})$. The pre-factor mobility of Coulomb scattering (μ_{RC}) can be derived with a formulation, $1/\mu_{mC}=1/\mu_{RC}\exp(-2k_FT_{int})$.

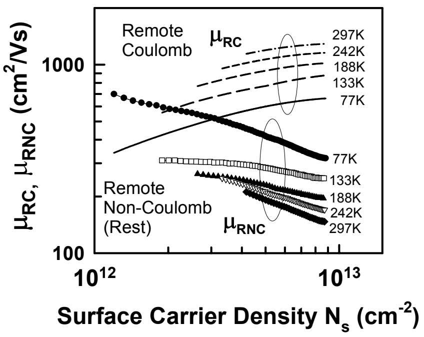

Fig. 6 Coulomb and non-Coulomb pre-factor mobility of $HfAlO_x$, as a function of N_s.

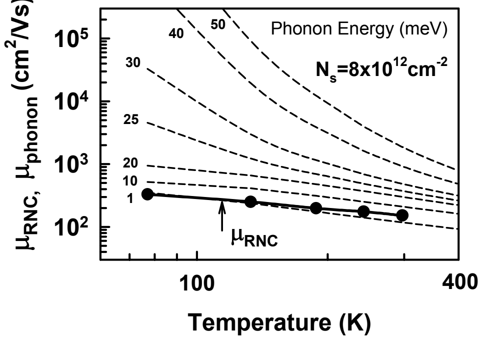

Fig. 7 Comparison of extracted non-Coulomb pre-factor mobility of $HfAlO_x$ at N_s=8x10^{12}cm^{-2} with the mobility of surface-optical phonon with various phonon energy. (Phonon energy is in terms of TO phonon.)