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 ($T_{int}=1.6, 2.6\text{nm in TEM}$) were grown on 12cm 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°C. 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 $\mu_m$ in the strong inversion can be expressed as [9]

$$1/\mu_m = (1/\mu_{nC}) \exp(-2k_FT_{int}) + 1/\mu_{nR}$$

where $k_F=\pi N_s$ is the Fermi wavenumber in the strong inversion ($N_s > 8\text{m}k_BT/\hbar^2$), $T_{int}$ is the thickness of an interfacial SiO$_2$ layer, and $\mu_{nR}$ is the universal mobility. From eq.(1), the slope of $1/\mu_m$ vs. $\exp(-2k_FT_{int})$ gives the pre-factor mobility of remote scattering $\mu_{nR}$.

Figure 2 shows a typical example of the measured mobility $\mu_m$ on n$^+$poly-Si/HfAlO$_x$/SiO$_2$ gate stacks [12]. The density of fixed charges as shown 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 optical phonons. The TO phonon energy producing a similar temperature dependence to $\mu_{nR}$ is less than 20meV. This result corresponds to the typical phonon energy for HfO$_2$-based materials as reported in Ref.[1].
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References
poly-Si and the fixed charges at the poly-Si/HfAlOx interface were
evaluated from the voltage drop across this interface, assuming
that the fixed charges were localized at the poly-Si interface. [14]
The phonon mobility $\mu_{\text{phonon}}$ was calculated with a relaxation time
approximation and a polar optical phonon scattering rate (D. K.
Ferry, “Semiconductors” p.221 (1991)), using the dielectric
constant and phonon energy of surface-optical phonons (Ref.[1]).

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

Fig. 2 Measured mobility on n+poly-Si/HfAlOx/SiO$_2$($T_{\text{int}}$)
n-channel MOSFETs with $T_{\text{int}}=1.6$, 2.6nm in 77 – 297K.

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

Fig. 4 Pre-factor mobility of HfAlOx $\mu_R$ as a
function of $N_s$, with temperature as a parameter.

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

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

Fig. 7 Comparison of extracted non-Coulomb pre-factor
mobility of HfAlOx 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.)