Projection of Mobility Degradation in HfAlO\textsubscript{x}/SiO\textsubscript{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\textsubscript{int}) will provide a physical basis for improving mobility in high-k MOSFET. Recent studies on the mobility of Al\textsubscript{2}O\textsubscript{3} MOSFETs \cite{1,2} indicate that the dominant carrier scattering mechanism is remote charge scattering (RCS), and that the mobility degradation with the reduction of T\textsubscript{int} can also be explained by RCS.

We study the mobility degradation of HfAlO\textsubscript{x}/SiO\textsubscript{2} nMOSFET, where another scattering mechanism might also contribute due to the presence of HfO\textsubscript{2} \cite{3}. In this paper we show that scattering rate originating from HfAlO\textsubscript{x}/SiO\textsubscript{2} films increases exponentially with the decrease of T\textsubscript{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\textsubscript{2} layers (T\textsubscript{int} =1.5, 2.0, and 3.0 nm) were first grown on 1\textmu cm p-Si(100) substrates at 950\textdegree C in 1% O\textsubscript{2}. Then, HfAlO\textsubscript{x} films were deposited with LL-D&A \cite{4}. About 0.8nm-thick HfAlO\textsubscript{x} film (Hf: 60at.%) was deposited, and subsequent in\textit{-situ} RTA was performed at 650\textdegree C in O\textsubscript{2} at 130Pa. This sequence was repeated to obtain 4nm-thick HfAlO\textsubscript{x}. Poly-Si gate nMOSFETs were fabricated using a conventional process with activation anneal in N\textsubscript{2} at 950\textdegree C for 20s. \textit{I\textsubscript{ds}}\textit{V\textsubscript{g}} and \textit{C\textsubscript{gs}}\textit{V\textsubscript{g}} (f=1kHz) were measured on W/L=190/500\textmu m FETs, and \mu -N\textsubscript{c} (N\textsubscript{c}: surface carrier density) or \textit{E\textsubscript{eff}} characteristics were evaluated from the split C-V method.

3. Results and Discussion

Figure 1 shows the experimental mobility of HfAlO\textsubscript{x}/SiO\textsubscript{2} (T\textsubscript{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\textsubscript{x}/SiO\textsubscript{2} film, \mu\textsubscript{ideal}, was evaluated as 1/\mu\textsubscript{ideal} = 1/\mu\textsubscript{meas} - 1/\mu\textsubscript{univ} where \mu\textsubscript{meas} and \mu\textsubscript{univ} are the measured and the universal mobility, respectively. A theoretical calculation of RCS based on Stern-Howard model \cite{5} was also performed, which includes a scattering potential with proper boundary conditions of the gate stack \cite{6}. From the experimental and calculated results in Fig. 2, we can assume that RCS is the major scattering in a lower N\textsubscript{c} region, while another scattering mechanism of the HfAlO\textsubscript{x}/SiO\textsubscript{2} film is predominant in a higher N\textsubscript{c} region.

Figures 3 and 4 show the scaling of the scattering rate from the gate dielectrics (\mu\textsubscript{ideal}) with the reduction of T\textsubscript{int}. The characteristic scaling length \lambda was evaluated as 1/\mu\textsubscript{ideal} \approx \exp(-T\textsubscript{int}/\lambda) \exp(-\textit{CE}/\lambda), as shown in Fig. 3, and the dependence of \lambda on N\textsubscript{c} is plotted in Fig. 4. It is found that \lambda at high N\textsubscript{c} (i.e. degenerate N\textsubscript{c}) is described as \lambda=1/(2\text{}\textmu)/\{1/(2\pi N\textsubscript{c})\}\textsuperscript{1/2}, while \lambda is a constant and around the thermal wave length at low N\textsubscript{c}. As shown in Fig. 5, the physics behind it is as follows: The scattering potential from the HfAlO\textsubscript{x}/SiO\textsubscript{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\textsubscript{c}) 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\textsubscript{int} is due to the boundary condition of Maxwell equation \cite{3,6}, and thus a similar dependence is also expected for other scatterings originating from the HfAlO\textsubscript{x}/SiO\textsubscript{2} interface.

From the experimental results and RCS simulation, we can predict the “ideal” mobility of HfAlO\textsubscript{x}/SiO\textsubscript{2} nMOSFET when RCS is completely eliminated. The ideal mobility, \mu\textsubscript{ideal}, was defined as 1/\mu\textsubscript{ideal} = 1/\mu\textsubscript{ideal} - 1/\mu\textsubscript{RCS} + 1/\mu\textsubscript{univ}. In Fig. 6 we show the projection of \mu\textsubscript{ideal} to various T\textsubscript{int} using the scaling rule of 1/\mu\textsubscript{ideal} \approx \exp[-T\textsubscript{int}/\lambda(N\textsubscript{c})] (the same dependence also assumed for 1/\mu\textsubscript{RCS}), and the \mu\textsubscript{ideal}N\textsubscript{c} relation at T\textsubscript{int}=1.5nm as a reference. The degradation of \mu\textsubscript{ideal} is predicted to be very severe with the reduction of T\textsubscript{int}, particularly at high N\textsubscript{c}. 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\textsubscript{x}/SiO\textsubscript{2} system.

4. Conclusions

The scattering rate from HfAlO\textsubscript{x}/SiO\textsubscript{2} films increases exponentially with the decrease of T\textsubscript{int}, and its characteristic scaling length is described with Fermi wave length at high N\textsubscript{c} (and thermal wave length at low N\textsubscript{c}). The scattering

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from the gate dielectrics includes non-Coulomb component, in addition to RCS. Based on these results, there is a concern that the mobility of HfAlOx nMOSFET degrades with the reduction of Tint, particularly at high Ns, even if RCS is completely eliminated.

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References