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Mobility Degradation and Interface Dipole Formation in Direct-Contact HfO_2/Si MOSFETs

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1. Introduction

Controlling interface dipoles in the high-*k* gate stack is a key issue for accurate V_{th} control of the advanced MOSFETs. However, disordered dipoles in gate stack structures degrade the charier mobility due to the fluctuated Coulomb potential [1]. The so-called direct-contact HfO_2/Si interface at which only about one monolayer Si oxide exists has a strong dipole layer (>0.5 V) [2], although this structure has an advantage in scaling EOT down to sub 1 nm [3]. V_{th} and mobility characteristics for the direct-contact HfO_2/Si structure have not been investigated in detail. In this paper, we first describe electrical characteristics of n-channel MOSFET with a direct-contact HfO_2/Si interface, and then discuss the effect of interface dipoles on the electron mobility.

2. Experimental

The n-MOSFETs were fabricated using a gate last process. To examine the dependence on the interface SiO_2 thickness in detail, a HfO_2/Gradually etched (GE) SiO_2/Si gate stack structure was integrated into the devices (Fig. 1). About 10-nm-thick SiO_2 layer was first thermally grown on the Si surface. The SiO_2 layer was then gradually etched by a diluted HF solution. A 2.6-nm-thick HfO_2 film was deposited on this surface by an ultra-high vacuum electron-beam evaporation method [3]. The postdeposition annealing (PDA) was performed at 400°C in 2×10^{-6} Torr O_2 pressure. Finally, a metal gate layer of iridium was deposited on the HfO_2 surface.

3. Results and Discussion

Well-behaved I_d-V_d characteristics were obtained from the direct-contact-HfO_2/Si MOSFETs as shown in Fig. 2. The I_d–V_g characteristics in Fig. 3 show an on/off ratio of about 10^5 and a subthreshold slope (S) of 72mV/decade. These data are quite normal, so we considered that our HfO_2 film works well as a gate dielectric, even though the direct-contact interface was employed. However, large negative V_{th} shift can be observed for the direct-contact structure; the direct-contact and stack structures have V_{th} of 0.16 V and 0.62 V, respectively. The split *C-V* curves shown in Fig. 4 show similar voltage shift. These *C-V* curves also show that the larger inversion capacitance can be obtained for the direct-contact structure. The EOT value was estimated to be 0.62 nm. Here, we assume that the thickness of interface SiO_2 layer (t_{IL}) in the HfO_2/SiO_2/Si stack structure corresponds to the EOT difference between the stack and direct-contact structures. The t_{IL} dependence of V_{th} shown in Fig. 5 indicates that negative V_{th} shift is effectively suppressed by insertion of a monolayer thick Si oxide (<1 nm) into the HfO_2/Si interface. Similar behavior has been observed for V_{fb} of MOS capacitors, as previously reported [2]. It was suggested from detailed analysis of the V_{fb} behavior that a strong dipole layer (>0.5 V) exists at the direct-contact HfO_2/Si interface, and it disappears with several monolayer thick Si oxides. Consequently, we concluded that similar dipole formation and annihilation take place at the HfO_2/Si interfaces in the present MOSFETs.

Electron mobility curves estimated for three types of interfaces are shown in Fig. 6. The mobility decreases with decreasing interface SiO_2 layer in the whole effective field range. In general, such t_{IL}-dependent degradation was explained by remote scattering mechanisms, e.g., remote Coulomb scattering by fixed charges in high-*k* layer and high-*k* phonon scattering [4-6]. To extract this additional mobility component (μ_{add}), the other scattering factors should be subtracted from measured mobility (μ_{mea}). In this study, mobility curve measured for the HfO_2/SiO_2/Si-stack MOSFET with thick t_{IL} (~5.4 nm) was used as a reference curve (μ_{ref}), and μ_{add} was estimated by Matthiessen's rule; $1/\mu_{add}=1/\mu_{mea}-1/\mu_{ref}$. The estimated μ_{add} curves are shown in Fig. 7. Typical bulk Coulomb and phonon scattering curves are also plotted, since it is expected that the remote scattering also have similar field dependence. This result suggests that at least both Coulomb and phonon scattering contributes to the t_{IL}-dependent degradation.

In general, remote scattering shows an exponential decay with decreasing interface SiO_2 layer [1,4,6]; $1/\mu_{add} \propto \exp(-2k_F t_{IL})$, where k_F is the Fermi wavenumber of channel electron and t_{IL} is the thickness of interface SiO_2 layer. Figure 8 shows the dependence of μ_{add} at 0.35 MV/cm on t_{IL}. μ_{add} decreases exponentially, and this tendency can be explained with the remote scattering process (solid line). If the dipoles induced at direct-contact interfaces largely degrade the mobility, it is expected to find some deviation from the remote scattering tendency. Figure 8 obviously indicates that the dominant degradation mechanism is remote scattering even for the direct-contact structures. It was proposed that Si-O chemical bonds at the HfO_2/Si interface are mainly responsible for the dipole formation [7]. It seems that such uniformly arrayed dipoles do not produce large Coulomb potential fluctuation which induces serious mobility degradation. Consequently, suppressing remote phonon scattering and eliminating fixed charges are important for improving electron mobility for direct-contact structures as well as for conventional stack structures.

4. Conclusion

The effect of dipole layer on the HfO_2/Si MOSFTE characteristics was investigated by using HfO_2/GE-SiO_2/Si structures. The direct-contact HfO_2/Si MOSFTEs showed serious electron mobility degradation. Its origin was ascribed to remote Coulomb and phonon scattering rather than the dipole scattering.

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References

[1] H. Ota *et al.*, IEDM Tech. Dig., 2007, p. 65.
[2] Y. Abe *et al.*, Appl. Phys. Lett. **90**, 172906 (2007).
[3] N. Miyata, Appl. Phys. Lett. **89**, 102903 (2006).
[4] M. V. Fischetti *et al.*, J. Appl. Phys. **90**, 4588 (2001).
[5] O. Weber *et al.*, Solid State Electron **50**, 626 (2006).
[6] N. Yasuda *et al.*, Jpn. J. Appl. Phys. **44** 7750 (2005).
[7] N. Miyata *et al.*, *APEX* **3**, 054101 (2010).

Process flow

- Si thermal oxidation (900°C, 10 nm)
- Gradual etching (diluted HF)
- HfO_2 deposition (EB, 2×10^{-6} torr O_2)
- PDA (400°C, 2×10^{-6} torr O_2)
- Metal gate deposition (Ir)

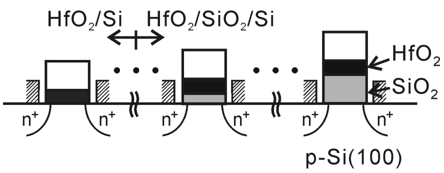

Fig. 1 Process flow of gate stack and fabricated HfO_2/GE-SiO_2/Si MOSFET structure.

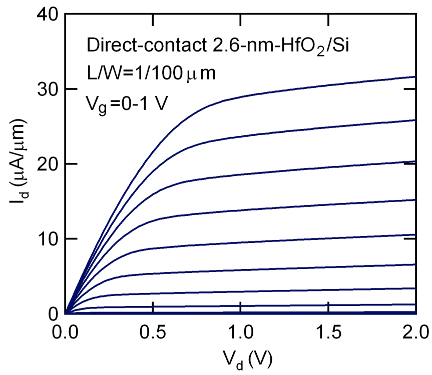

Fig. 2 I_d-V_d characteristics of direct-contact HfO_2/Si MOSFET. V_g was increased from 0 to 1.0 V in 0.1-V steps.

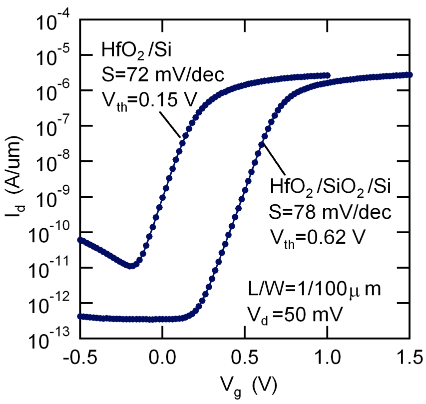

Fig. 3 I_d-V_g characteristics of direct-contact-HfO_2/Si and HfO_2/SiO_2/Si-stack MOSFETs. V_d was 50 mV.

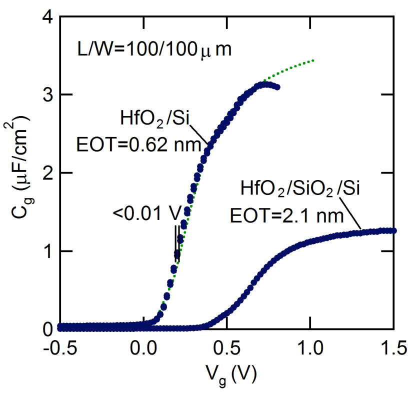

Fig. 4 *C-V* characteristics for direct-contact-HfO_2/Si and HfO_2/SiO_2/Si-stack MOSFETs.

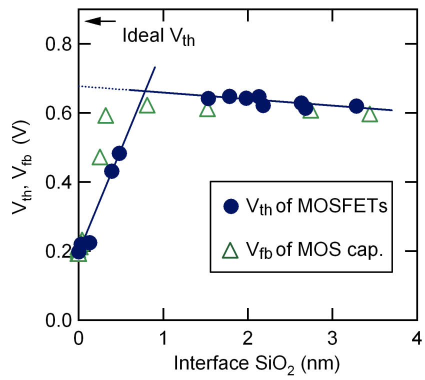

Fig. 5 Dependence of V_{th} on thickness of interface SiO_2 layer. V_{fb} of 2.5-nm-HfO_2/GE-SiO_2/n-Si MOS capacitors were also plotted as a reference.

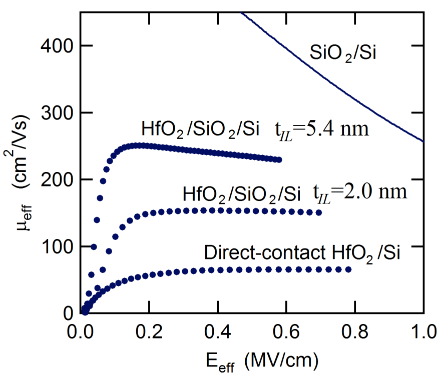

Fig. 6 Electron mobility characteristics of direct-contact HfO_2/Si and HfO_2/SiO_2/Si-stack MOSFETs.

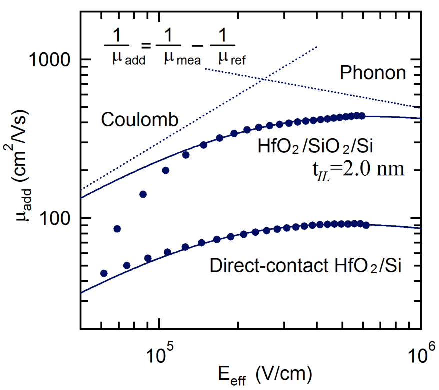

Fig. 7 Additional electron mobility (μ_{add}) caused by thinning of interface SiO_2 layer.

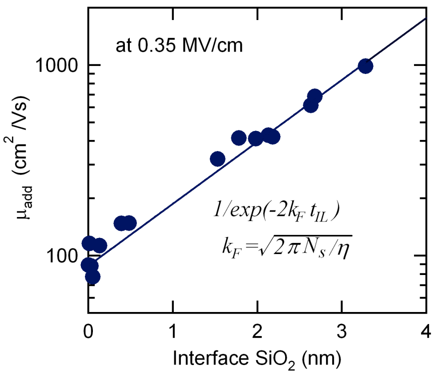

Fig. 8 Dependence of μ_{add} on thickness of interface SiO_2 layer (t_{IL}).