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Influence of pre-existing electron traps on drive current in MISFETs with HfSiON gate dielectrics

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Introduction

HfSiON is one of the promising candidates for alternative gate dielectrics because of its high thermal stability and excellent interface property compared to other high-k materials. However, HfSiON FETs show degradation of drive current with time under constant gate voltage conditions.[1] A transient charging phenomenon[2] is considered the cause of this degradation,[1] while the mechanism of this degradation has not been thoroughly understood. In this study, we focused on both V_{th} instability and mobility fluctuation due to charge trapping and investigated the contribution of the reduction in inversion carrier density (N_s) and the degradation of effective mobility (μ_{eff}) on the basis of pulsed measurement technique controlling a charge state of the traps.

Experimental

HfSiON FETs were fabricated by conventional CMOS process. HfSiON films were formed by MOCVD followed by plasma nitridation.[3] We prepared samples with Hf/Hf+Si ([Hf]) = 30% and 50%, changing the thicknesses of interfacial layer oxides (IL) shown in Table 1. EOT and V_{fb} of FETs without IL were almost the same irrespective of Hf concentration. In order to evaluate I_d with and without a transient charging phenomenon precisely, we used the measurement setup proposed by C.Leroux et al.[4] applying various voltage pulses to gate electrode.

Results and discussion

Fig.1 shows I_d transients in HfSiON N- and P-FETs without IL. In Fig.2, the change in I_d is plotted as a function of oxide field (E_{ox}) applied to gate insulator. Degradation of I_d in N-FETs was more significant than that in P-FETs and became severe with an increase in E_{ox}, which suggests that a transient charging phenomenon is closely related to trapping of electrons injected from inversion layer. It is also found that degradation of I_d for [Hf]=50% was more significant than that for [Hf]=30%. This result implies that a transient charging phenomenon in N-FETs limits the application of HfSiON with higher Hf concentration to CMOS devices. Therefore, we focused on HfSiON N-FETs with [Hf]=50% in the following discussion.

We first examined the influence of charge trapping on V_{th}. Trapping and detrapping characteristics were examined with several waveforms depicted in Fig.3, where base level voltage (V_{BL}) determined a initial charge state of the traps. Positive V_{th} shift induced by electron trapping became saturated in elapsed time of 10^2sec and such V_{th} shift was completely recovered by electron detrapping in the nearly equal elapsed time. We confirmed that the absolute value of V_{th} never changed before and after the measurement. These results imply that transient charging is caused by filling of pre-existing electron traps rather than generation of new defects. Then, we monitored relaxation process induced by sudden drop in gate voltage in order to investigate the location of the traps (Fig.4). Electrons released from gate insulator were detected even after 10^{-1}sec and the cumulative number of them reached to 1×10^{12}cm^{-2}. This density is much larger than interfacial trap density that is obtained with charge-pumping measurement (not shown), indicating that pre-existing electron traps are located at the deep inside of dielectrics. This interpretation is strongly supported by the fact that the time dependence of V_{th} shift and relaxation current is very similar to the prediction of the physical model[5] (Fig.3,4). Then, we conducted pulsed I_d-V_g measurement, retaining V_{BL} for enough time to reach equilibrium, and reducing the pulse width enough to prevent exchange of electrons (Fig.5). Positive V_{th} shift was induced by filling the traps at V_{BL}=+1.5V, where degradation of I_d is roughly equal to the loss of overdriving voltage. This indicates that reduction in N_s contributes to degradation of drive current. However, the influence of mobility degradation on degradation of drive current is still unclear. Then, we investigated the correlation between μ_{eff} and a charge state of the traps. We used the measurement setup which was modified to evaluate both ρ_{ch} and N_s. By using the waveforms illustrated in Fig.6(a), ρ_{ch} and N_s under a certain charge state of the traps were determined (Fig.6(b)). Fig.7 shows μ_{eff} and the effective density of charged states ($\Delta N_{ox} \equiv -C_{ox}\Delta V_{th}/e$) as a function of V_{BL}. ΔN_{ox} decreased monotonically with an increase in V_{BL}, while μ_{eff} reached a peak at V_{BL}~0V. This means that both trapping and detrapping of electrons increase the total number of charged states, resulting in the mobility degradation due to Coulomb scattering. However, change in a charge state of pre-existing electron traps has a negligible impact on μ_{eff} for HfSiON which is degraded considerably compared to μ_{eff} for SiO_2, as shown in Fig.8. The total mobility degradation in HfSiON N-FETs is strongly dependent on the physical thickness of IL (Fig.8), suggesting that remote Coulomb scattering (RSC) due to “fixed” charges inside HfSiON is the main cause of this degradation (Fig.9(a)(b)(c)). Inversion layer electrons are also affected by Coulomb scattering due to pre-existing traps inside HfSiON, while its contribution to the total mobility degradation in HfSiON N-FETs is relatively small since these traps are distributed far away from inversion layer compared to “fixed” charges (Fig.9(d)). It is clarified that mobility degradation due to electron trapping hardly contributes to degradation of drive current. However, assuming that pre-existing electron traps are intrinsic to HfSiON with higher Hf concentration, the influence of electron trapping on the mobility cannot be disregarded eventually.

Conclusions

A transient charging phenomenon is closely related to pre-existing electron traps in bulk HfSiON. Degradation of drive current due to this phenomenon is not attributable to mobility degradation but reduction in N_s caused by positive V_{th} shift. This degradation is more serious in N-FETs with higher Hf concentration. Design of the HfSiON gate stack aiming for the alleviation of transient charging effects is needed for the application to HfSiON CMOS devices.

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References

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Table 1 Physical parameters for gate stack with HfSiON prepared in this study. We also prepared SiO_2 gate insulator besides these samples.

Interfacial Oxide Thickness	HfSiON [Hf] : Hf/(Hf+Si)	HfSiON Thickness
-	30%	4.0nm
-	50%	5.0nm
1.7nm, 2.5nm, 4.0nm	50%	3.5nm

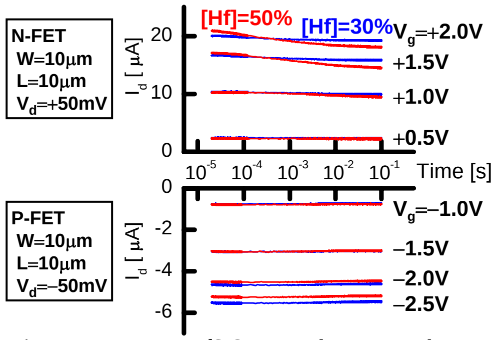

Fig.1 I_d transients in HfSiON N- and P-FETs with [Hf]=30% and 50%. EOT and V_{fb} are almost the same irrespective of Hf concentration.

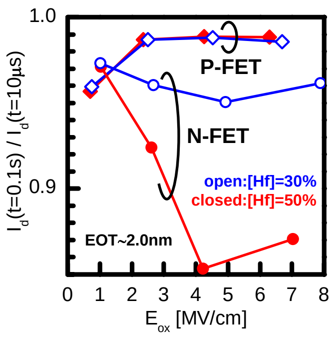

Fig.2 Oxide field (E_{ox}) dependence of change in I_d of HfSiON N- and P-FETs shown in Fig.1. N-FETs show severer degradation than P-FETs.

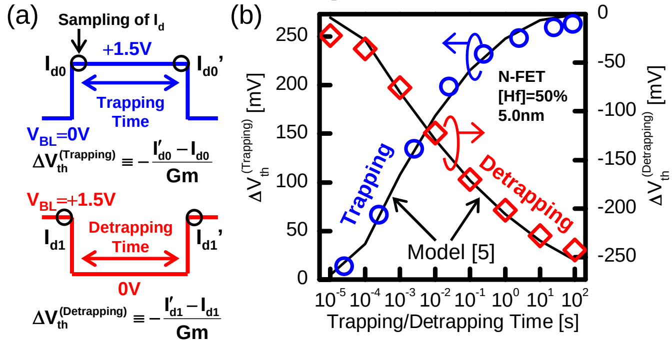

Fig.3 (a) Waveforms applied to gate electrode. V_{BL} determines a initial charge state of pre-existing electron traps. **(b)** V_{th} instability due to electron trapping and detrapping. Electron trapping shows saturation behavior. Trapped electrons are fully released and V_{th} shift is completely recovered.

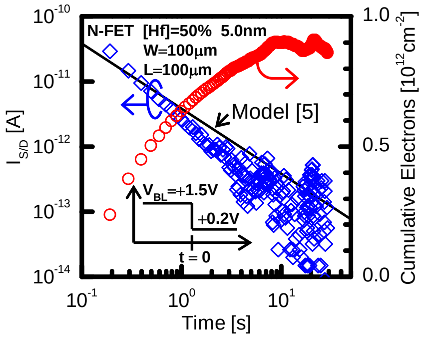

Fig.4 Relaxation current induced by sudden drop in gate voltage. $I_{S/D}$ is due to electrons released from the deep inside of dielectrics.

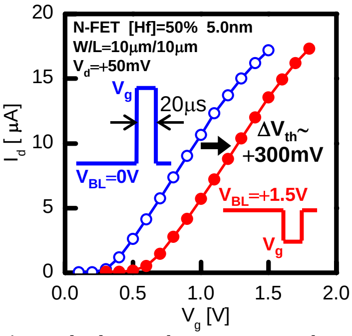

Fig.5 Pulsed I_d-V_g characteristics with different V_{BL}. A change in a charge state of pre-existing electron traps leads to V_{th} shift.

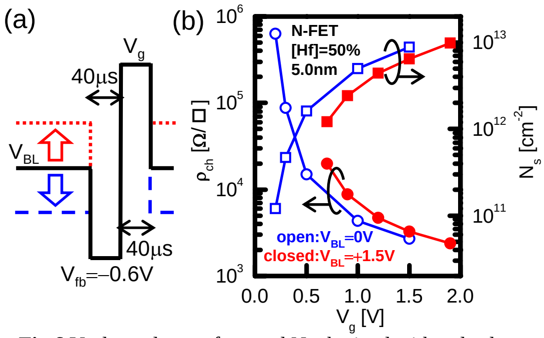

Fig.6 V_g dependence of ρ_{ch} and N_s obtained with pulsed measurement technique. A charge state of the traps can be controlled with V_{BL} arbitrary. Applying V_{fb}=–0.6V is necessary for the estimation of N_s, but pulse width is sufficiently short to maintain a charge state of the traps.

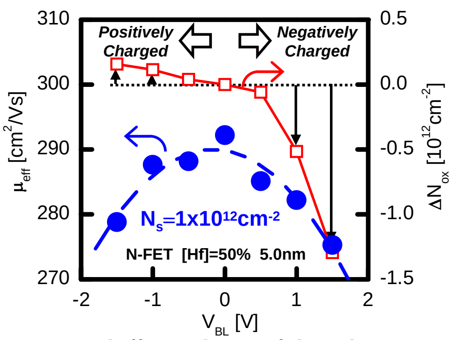

Fig.7 μ_{eff} and effective density of charged states (ΔN_{ox}≡–$C_{ox}\Delta V_{th}$/e) as a function of V_{BL}. μ_{eff} is modulated by variation in the occupancy of pre-existing electron traps in bulk HfSiON.

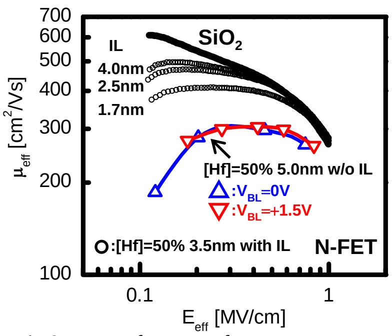

Fig.8 μ_{eff} as a function of E_{eff}. μ_{eff} appears to be insensible to V_{BL}, while remote Coulomb scattering (RCS) of "fixed" charges degrades μ_{eff} relentlessly.

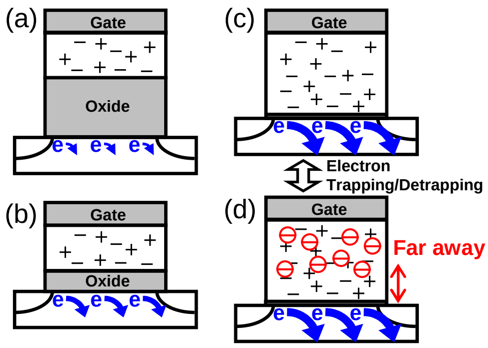

Fig.9 Schematic images of gate stacks with HfSiON representing possible scattering centers for inversion layer electrons. A lot of "fixed" charges degrade μ_{eff} considerably. The influence of pre-existing electron traps is relatively small because they are distributed far away from inversion layer.