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Effect of Coulomb Scattering on Stress-Induced Mobility Degradation in nMOSFETs with $HfAlO_X/SiO_2$ Dielectrics

W. Mizubayashi[1], N. Yasuda[2], H. Hisamatsu[2], H. Ota[1], K. Tominaga[2], K. Iwamoto[2], K. Yamamoto[2], T. Horikawa[1], T. Nabatame[2] and A. Toriumi[1, 3]

[1]MIRAI-ASRC, AIST Tsukuba West 7, 16-1, Tsukuba 305-8569, Japan
Phone: +81-29-849-1629 Fax: +81-29-849-1529 E-mail: w.mizubayashi@aist.go.jp
[2]MIRAI-ASET, AIST Tsukuba, Japan
[3]Department of Materials Science, The University of Tokyo, Japan

1. Introduction

Mobility degradation and reliability are most important issues of high-k gate dielectric technology. Since an interfacial dielectric layer is needed for the high-k gate stack structure, the high-k reliability should be significantly different from the uniform SiO_2 reliability so far extensively studied. In the double-layer dielectrics, the stress polarity is considered to affect the reliability in terms of defect generation rate and/or generation sites. In fact, the stress polarity dependence of the Weibull slope for Al_2O_3/SiO_2 dielectric structures has been reported[1]. The mobility is also seriously affected by the charge and/or defect in high-k dielectrics.

We have investigated the stress polarity dependence of the mobility degradation, because the mobility is very sensitive to the density and location of charged defects. In addition, the stress-induced mobility degradation is analyzed, since we think that it will be possible to characterize the mobility limited by the Coulomb scattering, which is considered to be the dominant scattering mechanism in the current high-k MOSFET, by extracting additional Coulomb scattering component observed in the mobility after electric stress.

2. Experimental

N^+-poly-Si gate n-MOSFETs with $HfAlO_X/SiO_2$ structures were fabricated. The interface SiO_2 was intentionally grown at 950°C from 1.5 to 3.0nm before high-k film deposition. 4nm thick $HfAlO_X$ (Hf:60at.%) was formed on the SiO_2 by layer-by-layer deposition and annealing (LL-D&A) method using TMA, $Hf[N(CH_3)_2]_4$ and H_2O[2]. The post deposition annealing was performed at 650°C in O_2. The source/drain activation annealing was performed at 950°C in N_2.

3. Results and Discussions

Fig. 1 shows effective motilities measured before and after a constant current stress as a function of effective field E_{eff} both for positive and negative bias stresses. Note that there is a significant mobility difference depending on stress bias polarities. In particular, the mobility in low E_{eff} region is severely degraded in the case of positive bias stressing. It is interesting to note that the mobility after negative bias stress is better than the initial one, presumably due to the release of electron or hole from the $HfAlO_X/SiO_2$ layer.

The current density in positive bias case is much larger than that in negative bias case, as shown in **Fig. 2**. The band diagram in negative and positive bias cases is shown

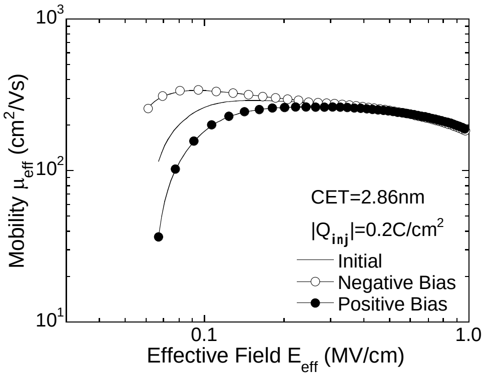

Fig. 1 The mobility before and after constant current stress as a function of effective field for $HfAlO_X/SiO_2$ with CET=2.86nm. The stress current density was $2x10^{-4}A/cm^2$ in both polarities. It is observed that the mobility degradation depends on the stress polarity. The mobility in E_{eff}<0.3MV/cm after positive bias stress is significantly degraded in comparison with the initial mobility.

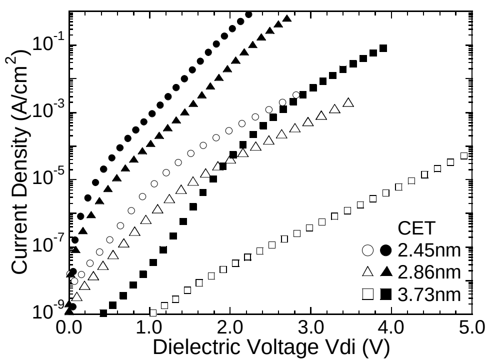

Fig. 2 The current density versus voltage across the dielectric film in $HfAlO_X/SiO_2$. The open symbol is for negative bias case, and the closed symbol is for positive bias one. The leakage current in the positive bias case is much larger than that in the negative bias one.

in **Fig. 3**. The electrons in negative bias are injected into both $HfAlO_X$ and SiO_2 films, while they can tunnel only through the SiO_2 in positive bias. The gate current in the positive bias should be higher than that in negative bias as observed in **Fig. 2**. In positive bias, electron energy is mainly dissipated in the $HfAlO_X$ conduction band, indicating that the trapped charges are generated in $HfAlO_X$ films. Thus, it is found that more significant degradation is attributable to electron or hole trapping in $HfAlO_X$ and/or $HfAlO_X/SiO_2$ interface in the positive bias stressing. On the other hand, from the results in **Fig. 1** and **3 (a)**, it is considered that the electron or hole in the initial trap sites are released in the case of the negative bias stress.

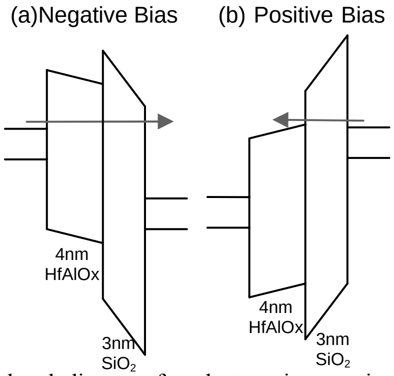

Fig. 3 The band diagram for electron in negative bias (a) and positive bias (b) for CET=3.73nm in $HfAlO_X/SiO_2$. The values of the band energy in $HfAlO_X$ are from the data in Ref. 5. The electron in positive bias passes the conduction band in $HfAlO_X$, indicating that the electron losses the energy at the conduction band in $HfAlO_X$.

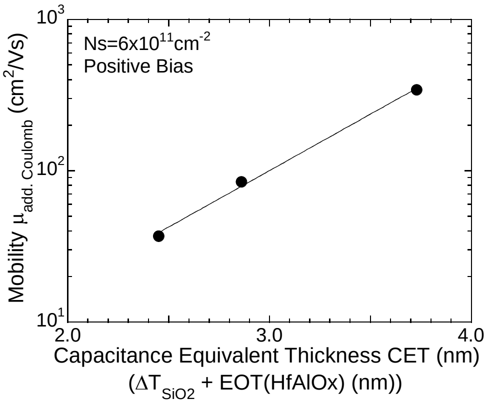

Fig. 4 The mobility of additional scattering after substrate injection stress is plotted as a function of capacitance equivalent thickness (CET) at N_S of $6x10^{11}cm^{-2}$. The effective field at stress is 7MV/cm. The CET is in proportion to interface SiO_2 thickness at a given $HfAlO_X$ thickness (4nm). The trapped charge exists mainly in the $HfAlO_X$ and/or $HfAlO_X/SiO_2$ interface.

Although the mobility degradation of high-k MOSFET is not fully understood, it is well known that the Coulomb scattering dominates the mobility degradation particularly at low E_{eff} region. To differentiate existing Coulomb scattering centers from additionally generated or annihilated ones under stress, a mobility component, $\mu_{add.Coulomb.}$, due to additional Coulomb scattering is extracted by using Matthiessen's rule;

$$1/\mu_{Stressed} = 1/\mu_{Initial} \pm 1/\mu_{add.Coulomb}, \quad (1)$$

where $\mu_{stressed}$ is the mobility after stress, and $\mu_{initial}$ is the initial mobility. By investigating $\mu_{add.Coulomb}$, it is possible to characterize the Coulomb scattering in high-k MOSFET.

Since the Coulomb scattering is expected to be sensitive to the distance between channel carriers and scattering centers, the interface SiO_2 thickness dependence of $\mu_{add.Coulomb}$ will clarify the characteristic distance due to the effect of the remote Coulomb scattering. **Fig. 4** shows $\mu_{add.Coulomb}$ as a function of the capacitance equivalent thickness (CET), which is exponentially proportional to the interface SiO_2 thickness (T_{SiO2}) in the case of a constant $HfAlO_X$ thickness (4nm):

$$1/\mu_{add.Coulomb} \propto 1/\tau_{a.C.} = C\exp(-\alpha \cdot CET) = C_0\exp(-\alpha \cdot T_{SiO2}), \quad (2)$$

where $\tau_{a.C.}$ is the additional scattering time, and C, C_0 and α are constants. The result in **Fig. 4** shows that the trapping center gets away from the channel in MOSFET as T_{SiO2} increases, which is consistent with the results in **Fig. 1** and **3(b)**, indicating that the trapped charge exists mainly in the $HfAlO_X$ and/or at the $HfAlO_X/SiO_2$ interface.

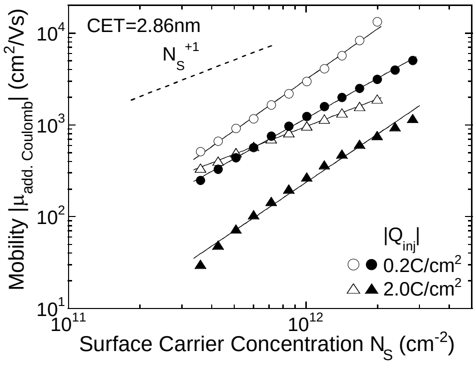

Fig. 5 The mobility limited by additional Coulomb scattering after both polarities stresses as a function of surface carrier concentration for CET=2.86nm. In both polarities, the stress current density $|J_{Stress}|$ was $2x10^{-4}A/cm^2$ for the case of the total-injected charge amount $|Q_{inj}|=0.2C/cm^2$, and the $|J_{stress}|$ was $2x10^{-3}A/cm^2$ for $|Q_{inj}|=2.0C/cm^2$. The $\mu_{add.\ Coulomb}$ follows the power law of N_S regardless of stress polarity.

In the Coulomb scattering, the screening effect is essential for the analysis. **Fig. 5** shows $\mu_{add.\ Coulomb}$ as a function of surface carrier concentration N_S. The results show a power law behavior as $\mu_{add.\ Coulomb} \propto N_S^m$, where m is a parameter describing the screening effect between 1 and 2 regardless of stress polarities and CET, which is larger than m≈1 for the substrate impurity scattering in the conventional MOSFET[3]. Recently, m=3 has been reported for the strained silicon mobility with HfO_2 gate dielectric[4]. These results might suggest that the screening effect works more efficiently in the Coulomb scattering of high-k MOSFETs.

4. Conclusions

We have investigated the effective mobility after electrical stress under both polarities for nMOSFETs with $HfAlO_X/SiO_2$ gate dielectrics. The stress polarity dependence of the mobility degradation has been reported for the first time, in which the positive bias stress causes more serious mobility degradation. Note that the positive bias case corresponds to the actual operation mode. The effective mobility limited by the Coulomb scattering in high-k MOSFETs is described by $\mu \propto \mu_0 N_S^m \exp(\alpha \cdot T_{SiO2})$, which means that the thinner interface layer might significantly degrade the mobility in low E_{eff}, but the high E_{eff} mobility limited by Coulomb scattering in operation mode will be sharply recovered by the screening effect.

Acknowledgements

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