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Electron Mobility Degradation Mechanisms in HfSiON MISFETs under the Real Operating Condition

Ryosuke Iijima, *Mariko Takayanagi, Takamitsu Ishihara, Takeshi Yamaguchi and Akira Nishiyama
Advanced LSI Technology Laboratory, Corporate Research & Development Center, Toshiba Corporation,
*SoC Research & Development Center, Toshiba Corporation Semiconductor Company
8, Shinsugita-cho, Isogo-ku, Yokohama 235-8522, Japan
Phone: +81-45-770-3693, Fax: +81-45-770-3578, E-mail: ryosuke.iijima@toshiba.co.jp

1. Introduction

For the application of high-k gate dielectrics, it is important to understand the mobility characteristics of MISFETs with high substrate impurity concentration (N_{sub}) in high surface carrier concentration (N_s) and high temperature regions. However, the systematic study has not been carried out yet under such conditions.

In this paper, for the first time, it is systematically proved that the electron mobility of HfSiON MISFETs with high N_{sub} in high N_s and high temperature regions is degraded by two scattering mechanisms. One is severe Coulomb scattering associated with charges in dielectrics and the other is scattering with soft phonon [1] in HfSiON.

2. Experimental

HfSiON N-MISFETs were fabricated by the conventional CMOS process. As a reference, N-MISFETs with SiO_2 were also fabricated by the same process. HfSiO films with the Hf/(Hf+Si) ratio of 50% were deposited on hydrogen-terminated Si substrates by MOCVD, followed by the nitrogen incorporation by Ar/N_2 plasma [2]. The nitrogen concentration is enough to suppress the phase separation on the basis of in-plane XRD spectra. The frequency dependence of the charge pumping current indicates that the interface trap density of HfSiON is about $5x10^{10}cm^{-2}eV^{-1}$ (Fig.1), which is so small that the influence of these traps on the mobility is negligible [3]. The dependence of the threshold voltage on the equivalent oxide thickness (EOT) indicates the existence of negative fixed charges near the interface (Fig.2). Their area density is about $1x10^{12}cm^{-2}$, which is not sufficiently small. Therefore, the influence of these fixed charges on the mobility cannot be ignored [4].

3. Results and discussion

At first, we examine the influence of scattering inherent to HfSiON, such as scattering with soft phonon that is expected to be apparent at high temperature. MISFETs with low N_{sub} ($3x10^{16}cm^{-3}$) were used in order to evaluate the effective mobility less affected by the substrate impurity in the wide range of the effective field (E_{eff}) [5]. Temperature was intentionally controlled from 223K to 473K, in order to systematically analyze the dominant scattering mechanism. Fig.3 shows the experimental mobility of HfSiON (μ_{HfSiON}) and that of SiO_2 (μ_{SiO2}) at various temperatures as a function of E_{eff}. It is clearly found that μ_{HfSiON} deviates from μ_{SiO2} at any temperature, which indicates that μ_{HfSiON} includes the additional mobility component ($\Delta\mu$) besides the mobility components composing μ_{SiO2}. Therefore, by using Matthiessen's rule, $\Delta\mu$ was extracted by the following equation. $\Delta\mu = (\mu_{HfSiON}^{-1} - \mu_{SiO2}^{-1})^{-1}$. Here, notice that plural scattering mechanisms responsible for the mobility degradation might contribute to $\Delta\mu$. Fig.4 shows $\Delta\mu$ at various temperatures as a function of N_s. It is found that $\Delta\mu$ at 223K significantly increases with an increase in N_s. This fact indicates that the mobility degradation at low temperature is mainly due to Coulomb scattering associated with charges in dielectrics [4,6], since the strong screening effects make the probability of Coulomb scattering small in the high N_s region [7]. In Fig.4, it is also found that the N_s dependence of $\Delta\mu$ varies with an increase in temperature. In order to analyze in detail, the temperature dependence of $\Delta\mu$ at low N_s ($2x10^{11}cm^{-2}$) and high N_s ($5x10^{12}cm^{-2}$) was plotted in Fig.5. It is found that $\Delta\mu$ at high N_s slightly decreases with an increase in temperature, which is contrary to the temperature dependence of $\Delta\mu$ at low N_s. If the mobility degradation is due to only Coulomb scattering, $\Delta\mu$ should increase with an increase in temperature irrespective of N_s, since the high average kinetic energy of inversion-layer electrons makes the probability of Coulomb scattering small at high temperature [7,8]. Therefore, these results shown in Fig.5 indicate that the mobility degradation is caused by another scattering inherent to HfSiON, especially in high N_s and high temperature regions. In addition, assuming that the screening effects at 473K are similar to these at 223K, Coulomb scattering hardly contributes to the mobility degradation in high N_s and high temperature regions. We consider this scattering inherent to HfSiON to be scattering with soft phonon in HfSiON.

Furthermore, we investigate the mobility characteristics of HfSiON MISFETs with high N_{sub} in high N_s and high temperature regions. Such conditions correspond to the actual CMOS operating conditions. Fig.6 shows μ_{HfSiON} and μ_{SiO2} at 473K of MISFETs with low N_{sub} ($3x10^{16}cm^{-3}$) and high N_{sub} ($3x10^{17}cm^{-3}$) as a function of E_{eff}. Then, $\Delta\mu$ extracted from this experimental mobility is plotted as a function of N_s (Fig.7). It is found that $\Delta\mu$ of MISFETs with high N_{sub} is lower than that of MISFETs with low N_{sub}. In MISFETs with high N_{sub}, inversion-layer electrons are confined in the steep triangle potential. In order to systematically investigate the relationship between $\Delta\mu$ and the configuration of the inversion layer, μ_{HfSiON} and μ_{SiO2} were measured under the substrate biasing conditions. The steepness of the triangle potential is determined by the surface concentration of the depletion charge (N_{dpl}), which was intentionally controlled by both N_{sub} and the substrate voltage (V_{sub}). Fig.8 shows $\Delta\mu$ as a function of N_s. Then, $\Delta\mu$ at high N_s ($5x10^{12}cm^{-2}$) is plotted as a function of N_{dpl} (Fig.9). It is found that $\Delta\mu$ depends only on N_{dpl} independent of the combination of N_{sub} and V_{sub}, which confirms that the lowering of $\Delta\mu$ shown in Fig.7 is caused by the increase in the steepness of the triangle potential. We consider this mechanism as follows. As the triangle potential becomes steep, the average position of inversion-layer electrons approaches the interface as shown in Fig.9 and consequently these electrons are more affected by Coulomb potential of charges in dielectrics. As a result, the electron mobility of HfSiON MISFETs with high N_{sub} in high N_s and high temperature regions is severely degraded by Coulomb scattering as well as scattering with soft phonon. Assuming that the decrease in $\Delta\mu$ shown in Fig.9 is mainly due to the degradation of the mobility limited by Coulomb scattering, it is estimated that the influence of Coulomb scattering is roughly comparable to that of scattering with soft phonon under the real operating condition. However, for the minute and quantitative analysis of the mobility determined by each scattering mechanisms, the further investigation is required.

4. Conclusions

By the systematic analysis, it is found that the electron mobility of HfSiON MISFETs with high N_{sub} in high N_s and high temperature regions is degraded by two scattering mechanisms. One is Coulomb scattering associated with charges in dielectrics, which is serious for electrons in the thin inversion layer. The other is scattering with soft phonon in HfSiON, which has a considerable impact on the mobility at high temperature.

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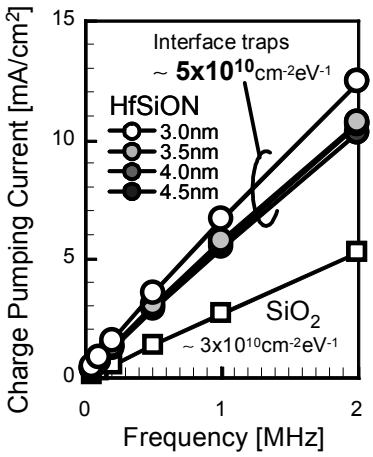

Fig.1 The frequency dependence of the charge pumping current.

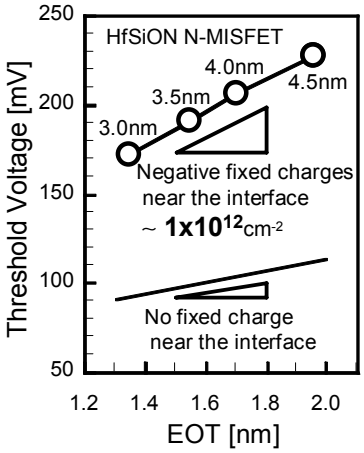

Fig.2 The EOT dependence of the threshold voltage defined as the gate voltage at N_s of $1x10^{11}cm^{-2}$.

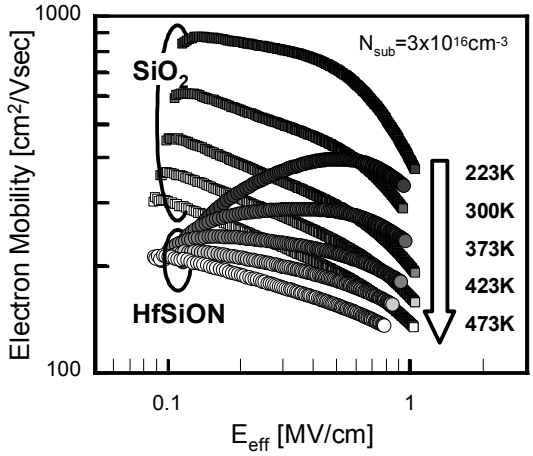

Fig.3 Experimental mobility of MISFETs with N_{sub} of $3x10^{16}cm^{-3}$ as a function of E_{eff} at temperatures from 223K to 473K.

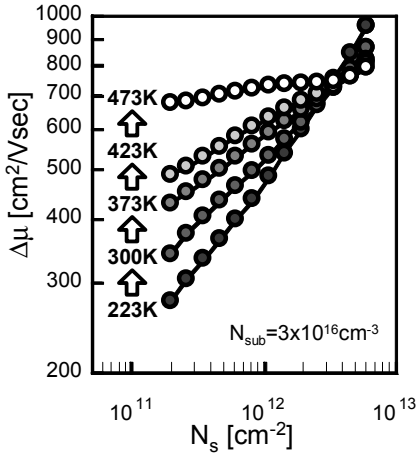

Fig.4 The additional mobility component Δμ of HfSiON MISFETs as a function of N_s at various temperatures.

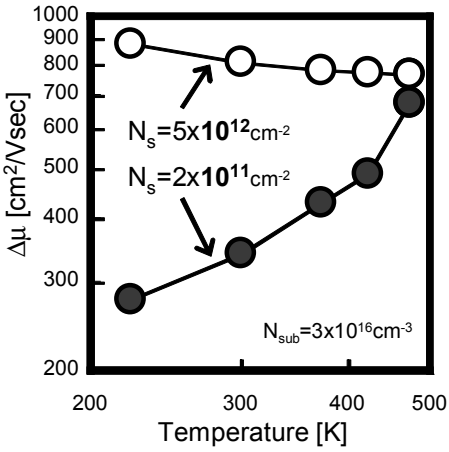

Fig.5 The temperature dependence of the additional mobility component Δμ of HfSiON MISFETs at low and high N_s.

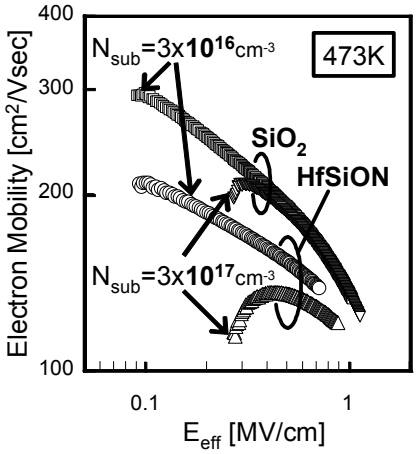

Fig.6 Experimental mobility at 473K of MISFETs with low N_{sub} ($3x10^{16}cm^{-3}$) and high N_{sub} ($3x10^{17}cm^{-3}$) as a function of E_{eff}.

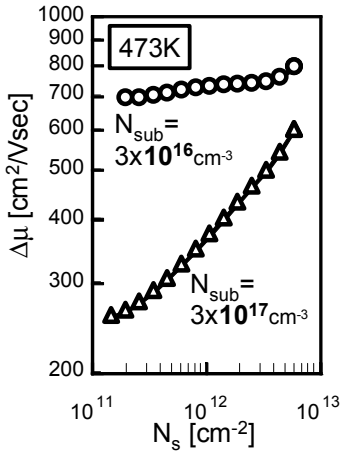

Fig.7 The additional mobility component Δμ of HfSiON MISFETs with low and high N_{sub} as a function of N_s.

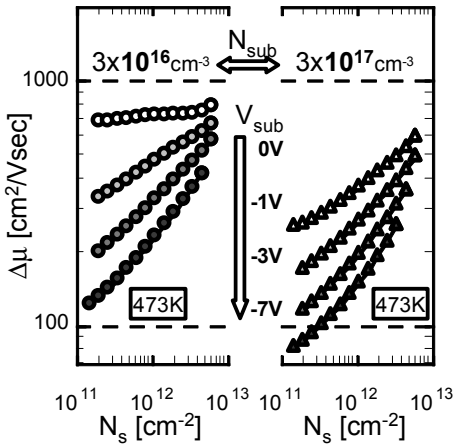

Fig.8 The additional mobility component Δμ of HfSiON MISFETs with low and high N_{sub} under the substrate biasing conditions as a function of N_s.

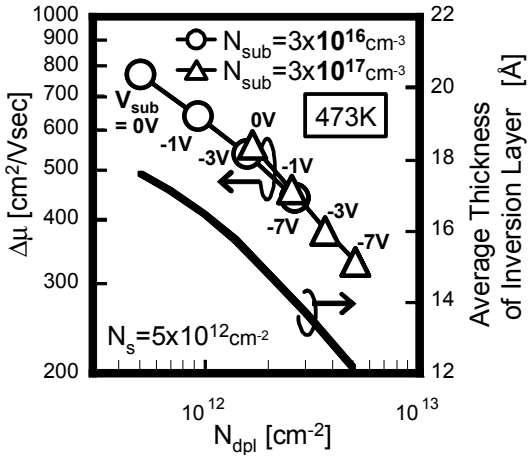

Fig.9 The additional mobility component Δμ of HfSiON MISFETs as a function of N_{dpl} controlled by both N_{sub} and V_{sub}. The average thickness of the inversion layer [6] is also plotted ,which was calculated with taking account of only the lowest sub-band.