Temperature Dependence of Channel Mobility in HfO_2-Gated NMOSFETs

W. J. Zhu, *Member, IEEE,* and T. P. Ma, *Fellow, IEEE*

***Abstract*—The degradation mechanisms of effective electron channel mobility in HfO_2-gated nMOSFETs have been studied by analyzing experimental data at various temperatures from 120 to 320 K. The major finding is that, while significant Coulomb scattering plays an important role in causing the observed mobility degradation, it does not account for all of the degradation; rather, it requires an extra phonon scattering mechanism, beyond that arising from the phonons in the Si substrate, to explain our experimental results. This extra phonon scattering mechanism has been found to exhibit relatively weak temperature dependence, and is attributed to the soft optical phonons in the HfO_2 layer.**

***Index Terms*—Channel mobility, Coulomb scattering, high-κ dielectrics, MOSFETs, phonon scattering.**

I. Introduction

To REALIZE the scaling scenario projected in the International Technology Roadmap for Semiconductors (ITRS), it is widely believed that a high-κ (high permittivity) dielectric is needed to serve as the CMOS gate dielectric to reduce significantly the gate leakage current [1]. After extensive research by numerous groups, several high-κ dielectrics have shown promising results [2]–[4]. However, there are still many challenges that have held back the actual implementation of these promising candidates. One of the major challenges is the significantly degraded channel mobility for high-κ gated MOSFETs compared to their SiO_2 counterparts [4], and there is not yet a clear understanding of the causes behind this degraded mobility. Coulomb scattering due to high density of interface trapped charges and fixed oxide charges in high-κ dielectrics appears to be an important contributor [5]. However, our preliminary analyzes of many high-κ samples have suggested that increased Coulomb scattering alone cannot account for all of the mobility degradation, and we believe that additional scattering mechanisms may be responsible for the difference. From a systematic study of the field dependence and temperature dependence of channel mobility in a set of HfO_2-gated nMOSFETs, we obtained strong evidence to support the "remote phonon" scattering mechanism, i.e., scattering by soft optical phonons in the high-κ dielectric, proposed by Fischetti, *et al.* [6]. This letter will report some of the key results that we have obtained through this study.

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W. J. Zhu was with Yale University, New Haven, CT 06520 USA. She is now with IBM Microelectronics, Hopewell Junction, NY 12533 USA (e-mail: wenjuan@us.ibm.com).

T. P. Ma is with Yale University, New Haven, CT 06520 USA.

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II. Accurate Channel Mobility Measurement

To study the scattering mechanisms, it is of crucial importance to accurately measure the channel mobility. In this letter, we obtained the effective channel mobility, $\mu_{\rm eff}$, from the drain current, I_d, in the linear region from the following equation [7]:

$$\mu_{\rm eff} = \frac{L}{W} \cdot \frac{I_d(V_g)}{V_d Q_{inv}(V_g)} \tag{1}$$

where the inversion charge density, $Q_{\rm inv}$, is usually extracted by measuring the gate-channel capacitance $C_{\rm gc}$ as a function of gate voltage, $V_{\rm g}$, by the split-capacitance-voltage (*C–V*) technique [8], and integrating

$$Q_{inv} = \int_{-\infty}^{Vg} C_{gc}(V_g)dV_g. \tag{2}$$

It has been shown that, because of significant trapping of carriers in high-κ gated MOSFETs, the use of the conventional split-*C–V* technique [9] will result in significant overestimate of $Q_{\rm inv}$, and thus a significant underestimate of the effective mobility [9]. Therefore, in this study we used a modified split-*C–V* technique [9] to obtain the $Q_{\rm inv}$ value accurately, which allowed us to extract the effective channel mobility accurately even in the presence of significant carrier trapping.

III. Device Fabrication and Measurements

Nonself-aligned nMOSFETs are fabricated with ultrathin [with equivalent oxide thickness (EOT) ~2 nm] HfO_2 gate dielectrics on p-Si substrates with a dopant concentration of approximately $4 \times 10^{15}/{\rm cm}^3$. The source and drain regions of the nMOSFETs are implanted with phosphorous. The implantation dose is $5 \times 10^{15}/{\rm cm}^2$, and the implantation energy is 80 keV. After source/drain activation at 1000 °C, thin HfO_2 films are deposited by jet-vapor deposition (JVD) [10], [11] at room temperature on HF-last Si substrates. The postdeposition anneal (PDA) is done in forming gas at 700 °C. Aluminum is used as the gate electrode and source/drain contacts. The split-*C–V* and I_d–V_g characteristics are measured at 320 to 120 K in a vacuum of 20 mTorr.

IV. Results and Discussion

Fig. 1 displays the effective mobility, $\mu_{\rm eff}$, of a HfO_2-gated nMOSFET measured at various temperatures from 120 to 320 K. For comparison, the universal mobility for SiO_2-gated nMOSFET is also shown in the same temperature range. In Fig. 1 the lowest set of curves, marked "HfO_2 w/o correction", was obtained by the use of the conventional split-*C–V* technique to get $Q_{\rm inv}$ from (2), which underestimates the effective mobility because of trapping. By the use of the modified split-*C–V*

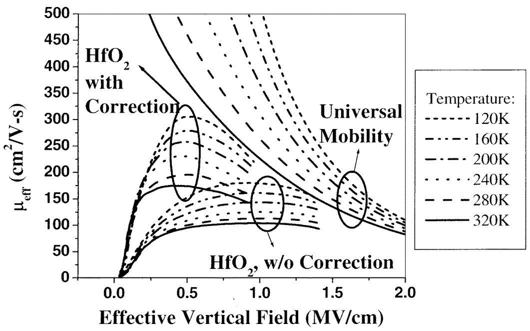

Fig. 1. Effective electron mobility in HfO_2-gated nMOSFET at various temperatures from 120 to 320 K, with and without interface-trap correction, as compared to universal mobility over the same temperature range.

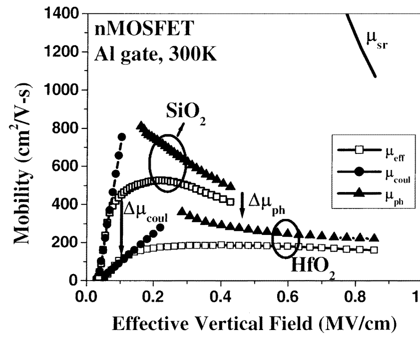

Fig. 2. Effective electron mobility, $\mu_{\rm eff}$, the mobility limited by Coulomb scattering, $\mu_{\rm coul}$, the mobility limited by phonon scattering, $\mu_{\rm ph}$, and that limited by surface roughness, $\mu_{\rm sr}$, for a HfO_2 sample and a SiO_2 sample, where the effective mobility, $\mu_{\rm eff}$, is extracted from split-*C–V* with interface-trap correction, $\mu_{\rm coul}$ is extracted from the effective mobility at low fields by linear fitting, $\mu_{\rm sr}$ is calculated according to (4), and $\mu_{\rm ph}$ is extracted according to (3). Note that $\mu_{\rm sr}$ is much higher than $\mu_{\rm coul}$ and $\mu_{\rm ph}$ in the field range of interest, and therefore $\mu_{\rm sr}$ does not affect $\mu_{\rm eff}$ significantly in this range.

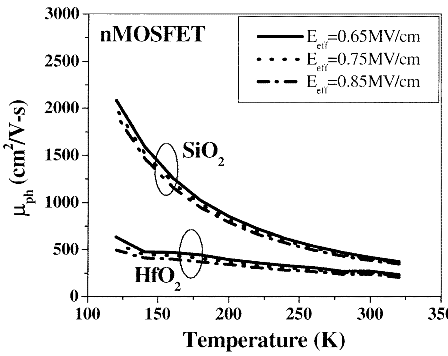

Fig. 3. Mobility limited by phonon scattering, $\mu_{\rm ph}$, for nMOSFET with HfO_2 or SiO_2 as gate dielectric at various effective electric fields from 0.65 mV/cm to 0.85 MV/cm.

technique to measure the $Q_{\rm inv}$ correctly, we obtained the set of curves marked "HfO_2 with correction" in Fig. 1, which is substantially higher than the uncorrected set, but is still much lower than that for the SiO_2-gated universal curves.

Fig. 2 shows the effective mobility as a function of effective field at 300 K for an nMOSFET with HfO_2 as gate dielectric and another one with SiO_2 as gate dielectric, both with Al gate. It is apparent that, at low fields the effective mobility of the HfO_2 sample is significantly lower than that of the SiO_2 sample, which may be attributed to the much stronger Coulomb scattering for the former due to its much higher trapped charge density (include interface traps, border traps [12] and bulk traps), as well as fixed oxide charge density. Here the Coulomb scattering includes possible remote coulomb scattering RCS [13] due to charges at some distances away from the dielectric/substrate interface. Note that in the low-field regime, the effective mobilities for these samples are approximately linearly proportional to the inversion charge density, which is consistent with the carrier screening effect [14].

In addition to Coulomb scattering caused by high densities of charges, the scattering due to soft optical phonons in high-κ dielectrics [6] is an intriguing possibility that cannot be overlooked. To analyze the possible phonon scattering effect, we make use of the following equation, according to Matthiessen's rule:

$$\frac{1}{\mu_{\rm ph}} = \frac{1}{\mu_{\rm eff}} - \frac{1}{\mu_{\rm coul}} - \frac{1}{\mu_{\rm sr}} \tag{3}$$

where $\mu_{\rm eff}$ is the total effective mobility $\mu_{\rm coul}$ is the mobility limited by Coulomb scattering, and $\mu_{\rm sr}$ is the mobility limited by surface roughness. To obtain the values for $\mu_{\rm ph}$, we extracted the values for $\mu_{\rm eff}$ from split-*C–V* with interface-trap correction, those for $\mu_{\rm coul}$ from the effective mobility at low fields by linear fitting [14] and then extrapolated to high fields, and $\mu_{\rm sr}$ by using the following equation [14]:

$$\mu_{sr} = B \cdot E_{\rm eff}^{-2.6} \tag{4}$$

where B is 4.5×10^{19}. The unit for $E_{\rm eff}$ is V/m, and the unit for $\mu_{\rm sr}$ is $\rm m^2/V - s$. Here we assume that the surface roughness for HfO_2 is similar to SiO_2, based on the fact that high-resolution transmission electron microscope (TEM) images of our HfO_2/Si samples show very smooth dielectrics/Si interface (data not shown), and the atomic force microscopy (AFM) images of our HfO_2 sample showed root-mean-square (rms) of 0.12 nm, suggesting that the surface roughness of the HfO_2 sample is comparable to its SiO_2 counterpart. In any case, in the mid-to-high field range we studied, the surface roughness scattering is much smaller than phonon scattering and Coulomb scattering, so any reasonable difference in $\mu_{\rm sr}$ will not impact significantly the extracted $\mu_{\rm ph}$ according to Matthiessen's rule.

Fig. 2 shows the extracted mobility limited by phonon scattering for a HfO_2-gated MOSFET and that for its SiO_2 counterpart. As we can see, the mobility limited by phonon scattering for the HfO_2-gated MOSFET is significantly lower than that for its SiO_2 counterpart, indicating a more severe phonon scattering for the former. Since the phonon scattering from the silicon substrate should be the same for both samples, this result suggests that the HfO_2-gated MOSFET has an additional source of phonon scattering, which is consistent with the high-κ related soft optical phonon model proposed by Fischetti [6].

The temperature dependence of the extracted mobility limited by phonon scattering, $\mu_{\rm ph}$, for HfO_2 and SiO_2 at various fields from 0.65 MV/cm to 0.85 MV/cm is shown in Fig. 3. Here the SiO_2 curves are calculated by using the equation: $\mu_{ph} = AE_{\rm eff}^{-0.3}T^{-1.75}$, where A is 2×10^5 in MKS unit [14]. As we can see, the mobility limited by phonon scattering for HfO_2 is much lower than that for SiO_2 for all temperatures we tested here, and the lower the temperature, the larger the degradation of $\mu_{\rm ph}$ for HfO_2 as compared to SiO_2.

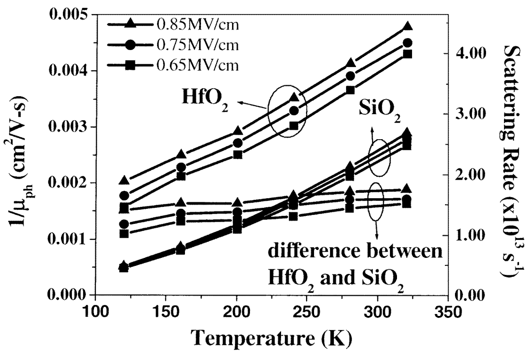

Fig. 4. Scattering rate due to phonons for nMOSFET with HfO_2 or SiO_2 as gate dielectric, indicating additional scattering in the HfO_2 sample as compare to the SiO_2 sample. The difference between the two is also plotted, and is attributed to scattering by soft optical phonons in HfO_2.

To investigate what may have caused the difference, we plot in Fig. 4 the reciprocal data of Fig. 3, or the phonon scattering rate as a function of temperature. Here the scattering rate is calculated according to the equation: Scattering_Rate $= (q/(\mu \cdot m^*))$, where m^* is the effective mass of the carrier in the Si inversion channel, and is taken to be $m^* = 0.91m_0$, where m_0 is the free electron mass. One can see that the phonon scattering rate for the HfO_2-gated sample is much higher than that for its SiO_2-gate counterpart. Since both the HfO_2-gated and the SiO_2-gated MOSFETs have essentially identical Si substrates, we attribute the difference in phonon scattering rates to other phonon sources, and the most likely source is the soft optical phonons in the high-κ gate dielectric, as proposed by Fischetti *et al.* [6]. By taking the difference between the two sets of curves in Fig. 4, one can get the scattering rate caused by this additional phonon source in the HfO_2 sample, and the resulting curves are also plotted in Fig. 4.

As one can see in Fig. 4, the scattering rate by the soft optical phonons in HfO_2 is a relatively weak function of temperature. The weak temperature dependence of the scattering rate for soft optical phonon can be qualitatively explained by the following derivation. In the two dimensional deformation potential theory of surface phonon scattering, the scattering rate due to optical phonon may be expressed as [15]

$$\frac{1}{\tau_{op}} \propto [N_R + (N_R + 1)u(E - \hbar\omega)] \qquad (5)$$

where $N_R = (1/(e^{\hbar\omega/kT} - 1))$ is the phonon occupation number, E is the carrier energy, ω is the phonon frequency, and u(x) is the unit step function, $u(x < 0) = 0$ and $u(x > 0) = 1$. Assume that the phonon energy is smaller than the thermal carrier energy (see discussion below), i.e., $\hbar\omega < E$, then

$$\frac{1}{\tau_{op}} \propto (2N_R + 1) = \frac{e^x + 1}{e^x - 1} \quad \text{where } x = \frac{\hbar\omega}{kT}. \qquad (6)$$

Equation (6) indicates that when $\hbar\omega \ll kT$, $(1/\tau_{op}) \propto T$, and when $\hbar\omega > kT$, $(1/\tau_{op})$ approaches a constant, i.e independent of temperature. For HfO_2, the soft optical phonon energies are 12.40 meV (TO1) and 48.35 meV (TO2) [6], which are to be compared to the kT range of 10.4 meV to 27.6 meV for our measurement temperatures (120 K to 320 K). Therefore, one would expect a temperature independent scattering rate for the TO2 phonons, and a constant-to-linear temperature dependence for the TO1 phonons, which is consistent with the weak temperature dependence shown in Fig. 4.

V. Summary

The degradation mechanisms of effective channel mobility in HfO_2-gated NMOSFETs have been studied at various temperatures from 120 to 320 K. We have found that, while significant Coulomb scattering does bring down the effective channel mobility substantially in high-κ gated NMOSFET, it cannot account for all of the mobility degradation as comapred to the universal mobility curve. A systematic study of the temperature dependence and field dependence of the effective mobility has led us to conclude that an additional scattering mechanism, that due to the soft optical phonons in the HfO_2 gate dielectric, may be responsible for the enhanced mobility degradation in HfO_2-gated MOSFETs. The scattering rate due to the soft optical phonons in HfO_2 has been found to be relatively weakly dependent on temperature, which is consistent with our simple theoretical calculation.

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