Electron mobility degradation due to Remote Coulomb scattering in Ge MOSFET

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Abstract—Remote Coulomb scatterings (RCS) on electron mobility degradation are experimentally investigated in Ge based metal-oxide-semiconductor field-effect-transistor (MOSFETs) with GeOx/Al2O3 gate stacks. The mobility is found increased with thicker GeOx (7.8-20.8 Å). The physical origin of this mobility dependence on GeOx thickness is explored: the following factors are excluded: Coulomb scattering due to interfacial traps at GeOx/Ge, phonon scattering, and surface roughness scattering. Therefore, the RCS from charges in gate stacks are studied. The charge distributions in GeOx/Al2O3 gate stacks are experimentally evaluated. The bulk charges in Al2O3 and GeOx are found negligible. The density of interfacial charge is +3.2×10^{12} cm^{-2} at GeOx/Ge interface, and -3×10^{12} cm^{-2} at Al2O3/GeOx interface. The electric dipole at Al2O3/GeOx interface is found +0.15 V, corresponding to areal charge density of 1.9×10^{13} cm^{-2}. The origin of this mobility dependence on GeOx thickness is attributed to the RCS due to electric dipole at Al2O3/GeOx interface. And this remote dipole scattering is found to play a significant role on mobility degradation. The discovery of this new scattering mechanism indicates that engineering of Al2O3/GeOx interface is key for mobility enhancement and device performance improvement. These results are helpful for understanding and engineering the Ge mobility enhancement.

Keywords—Ge; Mobility; Remote Coulomb scatterings;

I. INTRODUCTION

Ge semiconductor is rather potential as channel material in order to further equivalently scale down the metal-oxide-semiconductor field-effect-transistors (MOSFETs) beyond 10 nm technology node. For its successful application, a relevant parameter is effective channel mobility \( \mu_{\text{eff}} \) which is key point for Ge in replacement of Si substrate. The peak electron \( \mu_{\text{eff}} \) is experimentally found to be \( \sim 750 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \) using GeOx passivation and Al2O3 barrier layer, which gate structure has been considered as one of the most feasible routes for realizing both low density of interfacial states (D\text{\textsc{s}}) and low equivalent oxide thickness. Furthermore, to maximize the channel on-state current drivability, the scattering mechanisms that limit the \( \mu_{\text{eff}} \) are of great concern. Developing a process technology that improves the mobility requires understanding the mechanism of Ge mobility degradation. Several factors have been reported to induce mobility degradation, such as interfacial traps, surface roughness scattering, and oxygen atoms in Ge substrate. However, the mechanisms of Ge mobility degradation are still not fully clear. Especially the remote Coulomb scatterings (RCS) from Ge gate stacks are not reported to data, even though the RCS is found to play an important role in Si based MOSFETs with high-k materials. In this paper, the RCS is experimentally investigated for Ge MOSFETs. The RCS from electric dipole at Al2O3/GeOx interface is found to play a significant role on electron mobility degradation. This remote dipole scattering (RDS) indicates that the Al2O3/GeOx interface is critical for device performance enhancement.

II. EXPERIMENTAL

The Ge MOSFETs were fabricated as follows. The starting substrate is homemade 2 μm thick p-doped (100) epitaxial Ge on 8 inch p-doped (100) Si. The doping concentration is 10^{17} cm^{-3} for epitaxial Ge. After the cleaning of Ge surface by 100:1 H2O:HF for 60 s, the wafers were immediately capped with low temperature oxide SiO2 (~80 Å). Then source/drain region was opened by lithography-defined wet chemical etching, and the exposed Ge surface was again dipped in 100:1 H2O:HF for 60 s. After that the Ge surface was immediately subjected to remote oxygen plasma oxidation to form GeOx. Subsequently, Al2O3 was deposited by atomic layer deposition (ALD) using TMA and H2O as precursors at 300 °C. Then post deposition annealing (PDA) was performed at 400 °C in N2 for 5 min, followed by the ALD deposition of 3nm TiN and 75 nm W. After that, Ti source/drain contact and Al back contact were formed. Finally the wafers were subjected to the forming gas annealing at 400°C in 5% H2/95% N2 for 30 min. In addition, the MOS capacitors with Ge/GeOx/Al2O3/TiN/W gate stacks were also fabricated with the same process conditions with Ge MOSFETs.

III. RESULTS AND DISCUSSION

A. Mobility for different GeOx thicknesses

In order to investigate the remote Coulomb scattering, the mobility is evaluated as a function of the interfacial
GeO\textsubscript{x} thickness. Figure 1 shows the \textit{I}_d-\textit{V}_g characteristics of Ge nMOSFETs and electron mobility evaluated by the split capacitance-voltage (C-V) method at room temperature. Here four different thicknesses of GeO\textsubscript{x} interlayers were grown. From the Fig. 1(b), it can be seen that the mobility \( \mu \text{eff} \) at low inversion carrier density (\( N_s \)) increases with thicker GeO\textsubscript{x}. The mobility in our experiments is lower than bulk Ge substrate, because of the crystal quality of the epitaxial Ge\textsuperscript{[19]} However, all the samples were fabricated using same epitaxial Ge. As a result, this mobility dependence on GeO\textsubscript{x} thickness is also available. It should be stated that the series resistance due to source/drain is experimentally determined to be negligible for 100 \( \mu \)m gate length (less than 3\%), by using MOSFETs with different gate lengths (not shown here).

**FIG. 1.** (a) \textit{I}_d-\textit{V}_g of Ge nMOSFETs with Ge/GeO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3}/TiN/W gate stacks at room temperature. The Al\textsubscript{2}O\textsubscript{3} thickness is 10 nm. The GeO\textsubscript{x} thickness is given in the figure. (b) Electron mobility for different GeO\textsubscript{x} thicknesses.

### B. Exclusion of Dit as origin

In order to understand this phenomenon, the Dit is firstly evaluated for the four samples. Fig. 2 shows the C-V curves of Ge/GeO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3}/TiN/W MOS capacitors at 200 K and 100 K for 7.8 \( \text{Å} \) GeO\textsubscript{x}. The superior C-V characteristics are observed. Then the Dit are extracted by the low temperature conductance method for different GeO\textsubscript{x} thicknesses as shown in the Fig. 2(c). It can be seen that the Dit are nearly identical for different GeO\textsubscript{x} thicknesses. This is consistent with published reports that the Dit is nearly unchanged when GeO\textsubscript{x} thickness is larger than \( \sim 7 \text{ Å} \)\textsuperscript{[20],[21]} Thus the Dit can be excluded as physical origin of mobility dependence on GeO\textsubscript{x} thickness.

**FIG. 2.** C-V curves of Ge/GeO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3}/TiN/W MOS capacitors at (a) 200 K and (b) 100 K for 7.8 \( \text{Å} \) GeO\textsubscript{x}. The Dit is given in Fig. 2(c) for different GeO\textsubscript{x} thicknesses.

### C. Exclusion of remote phonon scattering as origin

Secondly the remote phonon scattering is considered. Fig. 3 shows the \textit{I}_d-\textit{V}_g characteristics and electron mobility at 77 K. It can be seen that the \( \mu \text{eff} \) still increases with thicker GeO\textsubscript{x}. Considering that the phonon scattering can be ignored at 77 K\textsuperscript{[22]} the remote phonon scattering can also be ruled out.

**FIG. 3.** (a) \textit{I}_d-\textit{V}_g and (b) electron mobility at 77 K.

### D. Exclusion of surface roughness scattering as origin

Thirdly the surface roughness scattering is studied. The root mean square (rms) of surface roughness is experimentally determined to be identical (\( \sim 0.3 \text{ nm} \)) for different GeO\textsubscript{x} thicknesses by atomic force microscope (AFM) (not shown here). Furthermore, the \( \mu \text{eff} \) at low \( N_s \) is mainly due to the Coulomb scattering but not surface roughness scattering.\textsuperscript{[23]} Consequently, the surface roughness scattering cannot account for this mobility dependence on GeO\textsubscript{x} thickness.

### E. Charge distribution in GeO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} gate stacks

Based on the above discussion, there is another scattering mechanism, and we consider the RCS as the possible origin. In order to further investigate the RCS, the charge distribution in the Al\textsubscript{2}O\textsubscript{3}/GeO\textsubscript{x}/Ge gate stacks is necessary to obtain. In our previous work, we experimentally extracted the charge distribution in Si gate stacks with high-k dielectric.\textsuperscript{[24]} Similarly, the charge distribution in the Al\textsubscript{2}O\textsubscript{3}/GeO\textsubscript{x}/Ge gate stacks can be extracted as follows. The flatband voltage (\( V_{FB} \)) of
$V_{fb} = \frac{Q_1}{\varepsilon_1} EOT + \frac{\varepsilon_1 \rho_1}{2\varepsilon_0} EOT^2$ \hspace{1cm} (1)

where $Q_1$ and $Q_2$ are areal charge densities at GeO$_x$/Ge and Al$_2$O$_3$/GeO$_x$ interfaces, respectively. The $\rho_1$ and $\rho_2$ are bulk charge densities in GeO$_x$ and Al$_2$O$_3$, respectively. The $\varepsilon_0$, $\varepsilon_r$, $\varepsilon_1$ and $\varepsilon_2$ are vacuum permittivity, relative permittivities of SiO$_2$, GeO$_x$ and Al$_2$O$_3$, respectively. The EOT is equivalent oxide thickness of whole gate stacks, and EOT2 is equivalent oxide thickness of Al$_2$O$_3$ dielectric. The $\Delta$ is $V_{FB}$ shift due to electric dipole at Al$_2$O$_3$/GeO$_x$ interface. A positive dipole is defined when positive charges appear at Al$_2$O$_3$ side and equivalent negative charges at GeO$_x$ side. The $\Phi_{ms}$ is the vacuum workfunction difference between TiN and Ge substrate. The Eq. (1) shows that the $V_{FB}$ is a quadratic function of EOT. And the $Q_1$ and $\rho_1$ can be extracted from the linear and quadratic terms of $V_{FB}$ vs. EOT plot. Fig. 4(a) shows the $V_{FB}$-EOT plot of TiN/10nm-Al$_2$O$_3$/terraced-GeO$_x$/Ge MOS capacitors at room temperature. It can be seen that a well linear fitted line can be obtained. Comparing the fitting result with the Eq. (2), the bulk charges $\rho_2$ in ALD Al$_2$O$_3$ can be determined to be 0 cm$^{-3}$. From the linear term in Eq. (2), the interfacial charges at Al$_2$O$_3$/GeO$_x$ interface ($Q_2$) can be determined to be $-2.3 \times 10^{12}$ cm$^{-2}$. The $\varepsilon_2$ is calculated to be 8.9 from Fig. 5(b). The dipole $\Delta$ is evaluated as follows. From Eq. (2) the intercept of $V_{FB}$-EOT plot is given as

$$\text{Intercept} = \frac{Q_1}{\varepsilon_1} EOT + \frac{\varepsilon_1 \rho_1}{2\varepsilon_0} EOT^2 + \Delta + \Phi_{ms}$$ \hspace{1cm} (3)

Then the $\Delta$ can be obtained if the intercept, EOT1 and $\Phi_{ms}$ are known. The intercept is -0.0009 V from the Fig. 5(a). The EOT1 is 1.75 nm from the intercept of EOT vs. Al$_2$O$_3$ thickness in Fig. 5(b). The vacuum workfunction of TiN has been experimentally determined to be 4.75 eV from TiN/terraced-SiO$_2$/Si MOS capacitors (not shown here). Considering the doping concentration in Ge substrate in our experiments, the $\Phi_{ms}$ can be calculated to be 0.03 eV. Then the interfacial dipole at Al$_2$O$_3$/GeO$_x$ interface can be determined to be +0.15 eV. Next, the charge density $Q_\Delta$ that induces this dipole is estimated. The dipole $\Delta$ can be expressed based on Gauss theorem

$$\Delta = \frac{Q_\Delta}{\varepsilon_5}$$ \hspace{1cm} (4)

The $T_\Delta$ is inner distance between positive and negative charges of dipole, and is taken as ~0.3 nm. The $\varepsilon_5$ is relative permittivity of the inner gap in dipole, and is taken as $2\varepsilon_1\varepsilon_2/((\varepsilon_1+\varepsilon_2)) \times 2\times 5.7 \times 8.9/(5.7+8.9) = 6.95$. Then charge density $Q_\Delta$ is calculated to be $1.9 \times 10^{13}$ cm$^{-2}$, which is about one order of magnitude larger than the interfacial charges ($Q_2$) at Al$_2$O$_3$/GeO$_x$ interface.
F. Remote dipole scattering

The remote Coulomb scattering is discussed. Based on the above results, three types of charges appear in the Al2O3/GeOx/Ge gate stacks: interfacial charges at GeOx/Ge interface (Q1), interfacial charges at Al2O3/GeOx interface (Q2), and electric dipole at Al2O3/GeOx interface (Δ). The Q1 cannot account for the mobility dependence on GeOx thickness in Fig. 1(b) and 3(b), because the scattering rate due to Q1 is identical for different GeOx thicknesses. The RCS due to Q2 can be negligible compared with RCS due to Δ, because the Q2 is one order of magnitude smaller than QΔ. Furthermore, the scattering rate due to RDS changes as exp(-2kFtIL) with interfacial GeOx thickness tIL,[29],[30] where kF is the Fermi wavenumber of the inversion electrons. Therefore, we can conclude that RDS is responsible for the mobility degradation with decreasing the GeOx thickness. Considering the exponential dependence of RDS on interlayer GeOx thickness, the RDS is a significant contribution of the mobility degradation in the ultrathin EOT region. From Fig. 1(b), the enhancement factor of peak mobility of 20.8 Å nm GeOx against the 12.1 Å GeOx is around 2. Fig. 6 schematically shows the scattering mechanisms for electron mobility. The RDS significantly reduces the mobility. Therefore, reduction or even elimination of this interfacial dipole should enable us to improve the electron mobility.

![Image of scattering mechanisms](image_url)

**FIG. 6. Schematic of the RDS on electron mobility.**

IV. CONCLUSIONS

In summary, the RCS for mobility degradation of Ge nMOSFET is experimentally investigated, and the electric dipole at Al2O3/GeOx interface plays a significant role on mobility degradation. Our findings indicate that understanding of the interface dipole at Al2O3/GeOx is critically important for mobility analysis. Engineering of this interface is a key for both mobility improvement and VFB tuning. The discovery of this new scattering mechanism in Ge based MOSFETs is helpful for further improvement of mobility and device performance.