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The temperature dependence of the electron mobility degradation mechanisms in n-channel metal-oxide-semiconductor field effect transistors with ZrO2 and Sm2O3 gate dielectrics

Hsiao-shuo Ho, Ingram Yin-ku Chang, and Joseph Ya-min Lee

Department of Electrical Engineering and Institute of Electronics Engineering, Tsing-Hua University, Hsinchu 30013, Taiwan, Republic of China

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The mobility degradation mechanisms of n-channel metal-oxide-semiconductor field effect transistors with ZrO2 and Sm2O3 gate dielectrics were studied. The temperature dependence of device characteristics was studied in the temperature range from 11 to 300 K. n-channel metal-oxide-semiconductor field effect transistors (MOSFETs) with SiO2 gate dielectric are used as reference. The electron mobility of ZrO2-gated n-MOSFETs is limited by Coulomb scattering. The extra source of Coulomb scattering is attributed to additional oxide trapped charges. The electron mobility in Sm2O3-gated n-MOSFETs is limited by phonon scattering. The extra source for phonon scattering is attributed to soft optical phonons in Sm2O3.

Recently, high-k gate dielectrics have attracted great attention. Zirconium oxide (ZrO2) and samarium oxide (Sm2O3) are considered as potential replacements of SiO2. ZrO2 has high dielectric constant (20–25),1–3 large energy band gap (5.4 eV), high breakdown electric field (7–15 MV/cm), high thermal stability, and low leakage current density.4 Sm2O3 has high dielectric constant (12–13), large energy band gap (4.33 eV), high breakdown electric field (5–7 MV/cm), high thermal stability, and low leakage current density.5–9 In the literature, several scattering sources have been reported in devices using high-k dielectrics.10–12 Zhu and Ma13 reported the degradation mechanisms of effective electron mobility in HfO2-gated n-channel-metal-oxide-semiconductor field effect transistors (MOSFETs) at various temperatures from 120 to 320 K. Chau et al.14 showed that the electron mobility degradation in HfO2-gated n-MOSFETs was due to surface phonon scattering. Casse et al.15 observed that the channel mobility degradation in HfO2-gated n-MOSFETs was from a remote Coulomb scattering due to fixed charges or dipoles at the HfO2/SiO2 interface. However, there are relatively few studies on the mobility degradation of ZrO2- and Sm2O3-gated MOSFETs, especially as a function of temperature.

In this work, n-MOSFETs with ZrO2 and Sm2O3 gate dielectrics were fabricated. The mobility degradation is characterized as a function of temperature.

For the mobility measurement of MOSFETs with ZrO2 gate dielectric, the effective mobility of MOSFETs \( \mu_{\text{eff}} \) can be written as

\[
\mu_{\text{eff}} = \frac{L}{W V_{\text{DS}} Q_{\text{INV}}(V_G)} I_D(V_G),
\]

The inversion charge density \( Q_{\text{INV}} \) was extracted by measuring the gate-channel capacitance \( C_{GC} \) as a function of gate voltage \( V_G \) using the split capacitance-voltage (C-V) technique.\(^{16} \) \( Q_{\text{INV}} \) is given by

\[
Q_{\text{INV}} = \int_{-\infty}^{V_G} C_{GC}(V_G) dV_G.
\]

The effective normal field \( E_{\text{eff}} \) can be expressed in terms of the depletion charge density \( \langle Q_d \rangle \) and the inversion charge density \( Q_{\text{INV}} \).\(^{15,17,18} \)
temperatures. Figure 2 shows the same for Sm2O3-gated transistors as a function of effective electric field at different intrinsic Fermi level temperature range from 11 to 300 K. The threshold voltage dependence of the threshold voltage was studied in the temperature range from 11 to 300 K. The threshold voltage does not increase linearly with decreasing temperature.

The effective electron mobility of ZrO2-gated transistors is plotted as a function of effective electrical field $E_{eff}$ in the temperature range from 11 to 300 K.

\[
E_{eff} = \frac{1}{e_{Si}} \left( |Q_d| + \frac{1}{2} |Q_{INV}| \right),
\]

where $|Q_d| + 1/2 |Q_{INV}|$ is the total silicon charge inside a Gaussian surface through the middle of the inversion layer.

Figure 1 shows the electron mobility of ZrO2-gated transistors as a function of effective electrical field at different temperatures. Figure 2 shows the same for Sm2O3-gated transistors. The electron mobility of ZrO2-gated transistors does not increase linearly with decreasing temperature.

For the mobility degradation mechanisms, the temperature dependence of the threshold voltage was studied in the temperature range from 11 to 300 K. The threshold voltage $V_T$ can be written as

\[
V_T = \phi_{ms} - \left( \frac{Q_m + Q_{at} + Q_f}{C_{ox}} \right) + 2\phi_f + \frac{1}{2} \frac{q\varepsilon_{Si}N_A\phi_f}{C_{ox}},
\]

\[\phi_f = \frac{kT}{q} \ln \left( \frac{N_A}{n_i} \right),\]

\[n_i = 3.9 \times 10^{16} T^{3/2} \exp(-E_g/2kT),\]

where $\phi_{ms}$ is work function difference between aluminum and silicon, $Q_f$ is fixed oxide charge, $Q_m$ is mobile ionic charge, $Q_{at}$ is oxide trapped charge, $Q_f$ is interface charged charge, $q\psi_f$ is energy difference between Fermi level $E_F$ and intrinsic Fermi level $E_i$ in silicon, $k$ is Boltzmann constant, $N_A$ is impurity concentration of the substrate, and $n_i$ is intrinsic carrier concentration. Because $\phi_{ms}$, $Q_m$, $Q_f$, and $Q_{at}$ are essentially temperature independent, differentiating Eqs. (4) and (5) with respect to temperature yields

\[
\frac{dV_T}{dT} = -\frac{1}{C_{ox}} \frac{dQ_{at}}{dT} + \frac{d\phi_f}{dT} \left( 2 + \frac{1}{C_{ox}} \sqrt{\frac{e_{Si}T^2 N_A}{\phi_f}} \right).
\]

From Eqs. (5) and (6),

\[
\frac{d\phi_f}{dT} = -\left( \frac{E_g}{2q} - \phi_f \right).
\]

The second term in Eq. (7) can be calculated using Eq. (8) and is about $-2.04$ mV/K for SiO2-gated transistors and $-1.98$ mV/K for ZrO2 and Sm2O3-gated transistors. Figure 3 shows the threshold voltage as a function of temperature for MOSFETs with different gate dielectrics. The slope ($\Delta V_T/\Delta T$) for SiO2-gated transistors is $-2.47$ mV/K. Similar value for Sm2O3-gated transistors is $-2.78$ mV/K and for ZrO2-gated transistors is $-3.47$ mV/K.

Comparing the calculated and experimental $\Delta V_T/\Delta T$ values, the ZrO2-gated transistors have a larger value of $\Delta V_T/\Delta T$, which is due to higher values of oxide trapped charges.

The Mathiessen’s rule [Eq. (9)] and the temperature dependence of inverse mobility [Eq. (10)] can be written as

\[
\frac{1}{\mu_{eff}} = \frac{1}{\mu_{ph}} + \frac{1}{\mu_{ns}} + \frac{1}{\mu_{cb}},
\]

\[
\frac{1}{\mu_{eff}} = \beta T^\gamma + \frac{\delta}{T},
\]

where $\mu_{ph}$, $\mu_{ns}$, and $\mu_{cb}$ represent the mobilities due to phonon scattering, surface roughness scattering, and Coulomb scattering, respectively. $\alpha$, $\beta$, $\gamma$, and $\delta$ are all positive and temperature-independent constants. Differentiating with respect to temperature $T$, one can find

\[
\frac{dV_T}{dT} = -\frac{1}{C_{ox}} \frac{dQ_{at}}{dT} + \frac{1}{C_{ox}} \frac{\phi_f}{\mu_{eff}},
\]

\[
\frac{d\phi_f}{dT} = -\left( \frac{E_g}{2q} - \phi_f \right).
\]

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\[
\frac{dV_T}{dT} = -\frac{1}{C_{ox}} \frac{dQ_{at}}{dT} + \frac{1}{C_{ox}} \frac{\phi_f}{\mu_{eff}},
\]

\[
\frac{d\phi_f}{dT} = -\left( \frac{E_g}{2q} - \phi_f \right).
\]
Figure 4 shows the temperature sensitivity factor value of ZrO$_2$-gate transistors is lower than that of SiO$_2$-gate transistors. The additional Coulomb scattering most likely comes from additional oxide trapped charges. Compared with SiO$_2$-gated transistors, the electron mobility of ZrO$_2$-gated n-MOSFETs is limited by Coulomb scattering at electric field above 0.33 MV/cm. This is most likely due to soft optical phonons in ZrO$_2$ layer. Comparing with SiO$_2$-gated transistors, the electron mobility of Sm$_2$O$_3$-gated n-MOSFETs is limited by additional phonon scattering at electric field above 0.22 MV/cm. The reason is most likely due to soft optical phonons in Sm$_2$O$_3$-gated n-MOSFETs.

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**References**