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Barrier Height Change in Very Thin SiO₂ Films Caused by Charge Injection

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In this paper, we report an investigation of barrier height change in gate oxide caused by charge injection. By analyzing the small change in the post-stress Fowler-Nordheim (FN) tunneling current through the oxide layer, the change of the oxide barrier height due to charge injection is determined quantitatively. The barrier height changes associated with different charge-injection directions and measurement polarities for n-channel metal oxide semiconductor field-effect transistors (MOSFETs) are presented. For comparison a measurement on a p-channel MOSFET is also carried out. For all the cases, the barrier height changes always exhibit a power law dependence on injected charge.

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It is well known that electric charges are injected into the gate oxide in a metal oxide semiconductor field-effect transistor (MOSFET) when the device is stressed at high electric fields. The charge injection can result in trap generation and charge trapping in the oxide and at the interfaces, leading to gate oxide degradation such as oxide leakage and breakdown. The charge trapping may cause changes of both the oxide barrier height and the oxide field. For unstressed devices, as the oxide field can be calculated accurately, the oxide barrier height can be obtained from the amplitude of the Fowler-Nordheim (FN) tunneling current across the oxide layers as predicted by the FN theory. However, for stressed devices, both the oxide field and the oxide barrier height may be changed by the charge trapping. Therefore, the conventional FN plots (i.e., in J/E₀ vs. J/E₀ where J is the FN tunneling current and E₀ is the externally applied oxide electric field) cannot yield a reliable barrier height. Obviously, a systematic study of the changes of both the oxide field and the oxide barrier height as a function of charge injection is highly desirable. In this work, we used a novel approach to analyze the change in the FN tunneling current through the oxide layer caused by high field stress, and thus the change of the oxide barrier height is obtained. The barrier changes in n-channel MOSFETs associated with different charge-injection directions and measurement polarities are determined. In addition, for comparison the barrier height change in a p-channel MOSFET caused by positive-charge stress is also measured with positive-charge current-voltage (I-V) measurement. For all the cases, the barrier height change is found to follow a power law of the form Q<sup>n</sup> with n ≈ 0.1 to 0.4 where Q<sub灌</sub> is the injected charge dose.

**Experimental**

The n<sup>-</sup>-polysilicon-gate n-channel and p<sup>-</sup>-polysilicon-gate p-channel MOSFETs used in this study were fabricated in a manufacturing facility by a 0.25 μm process with a channel length of ~0.25 μm and a gate width of 50 μm. The gate oxide thickness was 4 nm. The n-channel devices were stressed with FN injection from the gate electrode (i.e., the gate injection under negative gate bias) or from the substrate (i.e., the substrate injection under positive gate bias) at a constant current (10 mA/cm²) (the source, drain, and substrate were grounded). On the other hand, the p-channel device was stressed under positive gate bias with the same current density. After each FN stress, a negative or positive I-V measurement was conducted. Both the stress and the I-V measurement were carried out with an HP4156A semiconductor parameter analyzer at room temperature. The stress caused a small change in the FN tunneling current. The stress effect can be seen clearly in the plots of E₀ ln(J/J<sub灌</sub>) vs. J/E₀ where E₀ is the externally applied oxide field, and J<sub灌</sub> and J are the FN tunnel currents before and after stress, respectively. Figure 1 shows a typical example of E₀ ln(J/J<sub灌</sub>) vs. J/E₀ as a function of injected charge.

**Results and Discussion**

As discussed below, by analyzing the change of the I-V characteristics in the FN tunneling regime, the oxide barrier height change can be determined. The relationship between the FN tunneling current (J) through the oxide layer and the oxide field (E<sub灌</sub>) can be expressed by the following well-known formula

\[ J = AE_0^2 \exp(-B/E_0) \]

where A and B are two constants given by

\[ A = \frac{q^2 m_{Si}}{8 \pi \hbar m_{o} \Phi_b} \]

\[ B = \frac{4}{3} \frac{(2 m_{o})^{1/2}}{q \hbar} \Phi_b^{3/2} \]

where q is the electronic charge, m<sub>Si</sub> and m<sub>o</sub> are the effective electron mass in Si and SiO₂, respectively, h is the Planck constant, \( \Phi_b \) is the oxide barrier height. When electric charges are injected into the oxide under high field stress, the charge trapping in the oxide and at the interfaces may lead to a change (ΔE) of the oxide field. Now the oxide field at the tunneling

![Figure 1. Typical E₀ ln(J/J₀) vs. J/E₀ as a function of injected charge dose.](image-url)
interface $E_{ox} = E_0 (1 + \Delta E/E_0)$, where $E_0$ is the externally applied oxide field as mentioned above. On the other hand, the stress could also lead to a change ($\Delta A$ and $\Delta B$) in the A and B values if the oxide barrier height is changed by the stress. From Eq. 2 and 3, if the changes are small, it can be shown that
\[
\frac{\Delta A}{A_0} = -\frac{\Delta \Phi_b}{\Phi_{so}}
\]
[4] and
\[
\frac{\Delta B}{B_0} = \frac{3}{2} \frac{\Delta \Phi_b}{\Phi_{so}}
\]
[5]
where $\Phi_{so}$ is the $\Phi_s$ value before stress and $\Delta \Phi_b$ is the oxide barrier height change, and $A_0$ and $B_0$ are the A and B values before stress, respectively.

From Eq. 1, we obtained the following expression for the comparison of the FN tunneling current ($J$) after stress with the tunneling current ($J_0$) before stress in terms of the changes $\Delta E$, $\Delta A$, and $\Delta B$
\[
\ln \left( \frac{J}{J_0} \right) = \ln \left( 1 + \frac{\Delta A}{A_0} \right) + 2 \ln \left( 1 + \frac{\Delta E}{E_0} \right) + \frac{\Delta E}{E_0} - \frac{\Delta B}{B_0}
\]
[6]
Inserting Eq. 4 and 5 into Eq. 6, and if $\Delta E/E_0$ and $\Delta \Phi_b/\Phi_{so}$ are small, one can obtain
\[
\ln \left( \frac{J}{J_0} \right) \approx - \left( 1 + \frac{3}{2} \frac{B_0}{E_0} \right) \frac{\Delta \Phi_b}{\Phi_{so}} + \frac{2 B_0}{E_0} \frac{\Delta E}{E_0}
\]
[7]
As $(3/2)(B_0/E_0) \gg 1$, Eq. 7 can be also expressed approximately as
\[
E_0 \ln \left( \frac{J}{J_0} \right) \approx - \frac{3}{2} \frac{\Delta \Phi_b}{\Phi_{so}} B_0 - 2 \Delta E + \frac{(B_0 \Delta E)}{E_0}
\]
[8]
Because $B_0$, $\Delta E$, and $\Delta \Phi_b/\Phi_{so}$ are independent of the $E_0$, a linear relationship is expected in the plot of $E_0 \ln(J/J_0)$ vs. $1/E_0$. This has been confirmed by our measurements (one typical example is shown in Fig. 1). Based on Eq. 8, a linear regression to the data points of $E_0 \ln(J/J_0)$ vs. $1/E_0$ yields the values of both $\Delta E$ and $\Delta \Phi_b/\Phi_{so}$. This method enables us to quickly determine the barrier height change and the oxide field change simultaneously.

The oxide barrier height change resulting from different injection directions (gate or substrate injections) and measured with different gate-bias polarities (i.e., the positive and negative I-V measurements) has been determined by using the above approach. The barrier height changes in n-channel MOSFETs of different situations are shown in Fig. 2 and 3. Figure 2 shows the barrier height change $\Delta \Phi_b/\Phi_{so}$ vs. the injected charge dose $Q_{inj}$ for the gate injection measured with the negative I-V (Fig. 2a) and positive I-V (Fig. 2b) measurements, and Fig. 3 shows the $\Delta \Phi_b/\Phi_{so}$ vs. the $Q_{inj}$ for the substrate injection measured with the negative I-V (Fig. 3a) and positive I-V (Fig. 3b) measurements. For comparison, the barrier height change in a p-channel MOSFET caused by positive-polarity stress is also measured with positive-polarity I-V measurement as shown in Fig. 4. As can be seen in all these figures (note that $\Delta \Phi_b/\Phi_{so}$ vs. $Q_{inj}$ is plotted in log-log scale), the $\Delta \Phi_b/\Phi_{so}$ follows
a sublinear power law, i.e., $\Delta \Phi_p/\Phi_{50} = A Q_{inj}^n$, where $A$ and $n$ are two coefficients that are generally different for different stresses and devices. We have examined many identical devices as well as different devices with different dimensions for different injection directions/measurement polarities. For all the cases, the power-law behavior was always observed with the exponent factor $n \approx 0.1$ to 0.4. It seems that there was a trend that positive I-V measurement had a higher $n$ value and that the $n$ was also larger for gate injection. The reason for this trend is not clear yet. On the other hand, it was found that the $\Delta E$ (and thus the charge trapping) also exhibited a power-law behavior with an $n$ value almost identical to that of the barrier height change. This implies the strong relationship between the charge trapping and the barrier height change.

**Conclusions**

We have conducted an investigation of barrier height change in gate oxide caused by charge injection. By analyzing the small change in the post-stress FN tunneling current through the oxide layer, the changes of the oxide barrier heights due to charge injection are determined quantitatively. The barrier height changes associated with different charge-injection directions and measurement polarities are determined for n-channel MOSFETs. For comparison a measurement on a p-channel MOSFET is also carried out. For all the cases, the barrier height change always exhibits a power-law dependence on injected charge with the power-law exponent factor $n \approx 0.1$ to 0.4. It is also observed that gate injection and positive I-V measurement tend to yield a higher $n$ value. The oxide field change (and thus the charge trapping) also exhibits a power-law behavior almost identical to that of the barrier height change, implying the strong relationship between the charge trapping and the barrier height change.

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