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Barrier Height Change in Very Thin SiO_2 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.[1-6] 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.[7,8] 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.*, ln J/E_0^2 *vs.* $1/E_0$ where J is the FN tunneling current and E_0 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 height 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-polarity stress is also measured with positive-polarity current-voltage (I-V) measurement. For all the cases, the barrier height change is found to follow a power law of the form Q_{inj}^n with $n \approx 0.1$ to 0.4 where Q_{inj} is the injected charge dose.

Experimental

The n^+-polysilicon-gate n-channel and p^+-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/cm^2) (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 $E_0 \ln(J/J_0)$ *vs.* $1/E_0$ where E_0 is the externally applied oxide field, and J_0 and J are the FN tunnel currents before and after stress, respectively. Figure 1 shows a typical example of $E_0 \ln(J/J_0)$ *vs.* $1/E_0$ 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_{ox}) can be expressed by the following well-known formula[7]

$$J = AE_{\mathrm{ox}}^2 \exp(-B/E_{\mathrm{ox}}) \quad [1]$$

where A and B are two constants given by

$$A = \frac{q^3 m_{\mathrm{Si}}}{8\pi h m_{\mathrm{ox}} \Phi_{\mathrm{b}}} \quad [2]$$

$$B = \frac{4}{3} \frac{(2m_{\mathrm{ox}})^{1/2}}{q\hbar} \Phi_{\mathrm{b}}^{3/2} \quad [3]$$

where q is the electronic charge, m_{Si} and m_{ox} are the effective electron mass in Si and SiO_2, respectively, h is the Planck constant, $\hbar$ the reduced Planck constant, and Φ_{b} 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

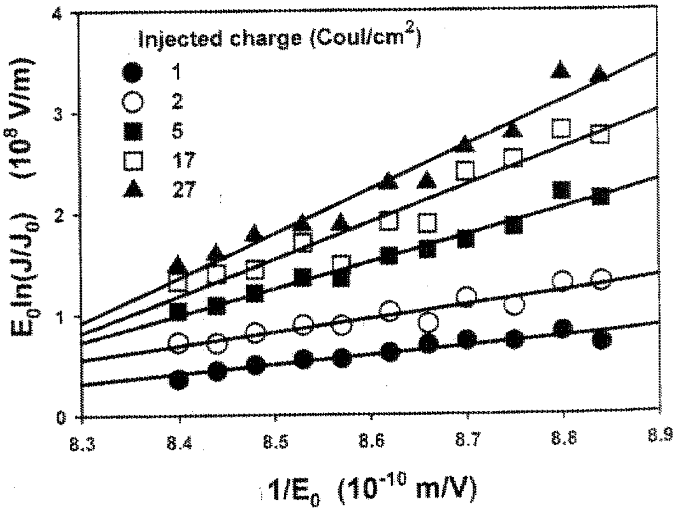

Figure 1. Typical $E_0 \ln(J/J_0)$ *vs.* $1/E_0$ as a function of injected charge dose.

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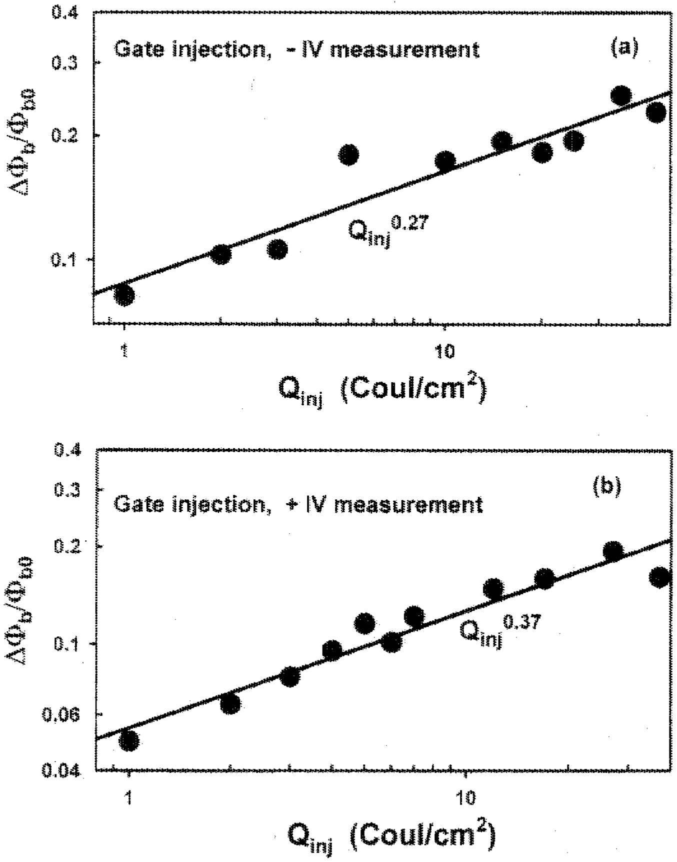

Figure 2. Oxide barrier height change ($\Delta\Phi_b/\Phi_{b0}$) in an n-channel MOSFET *vs.* charge injection (Q_{inj}) for gate injection. (a) Negative and (b) positive I-V measurement.

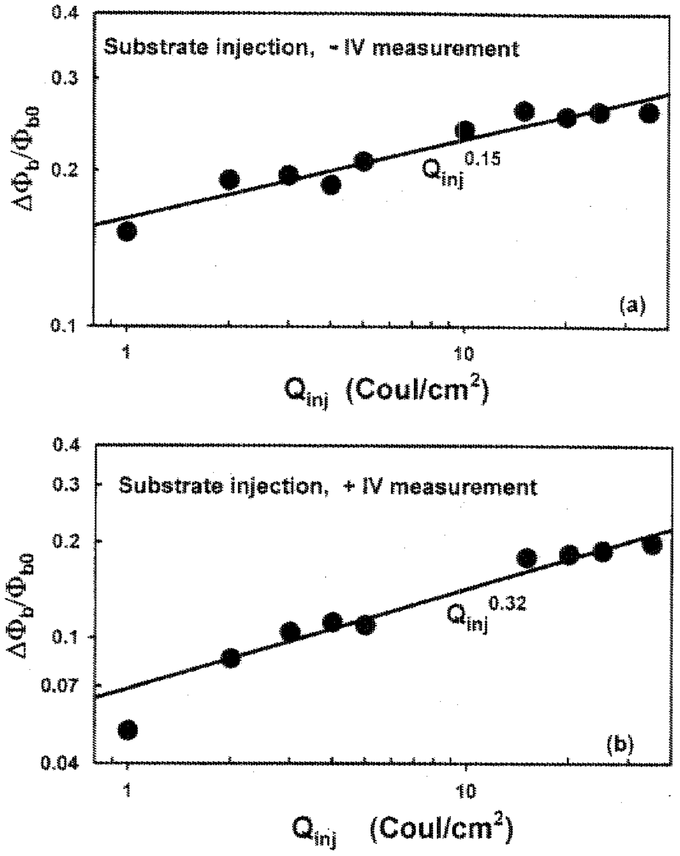

Figure 3. Oxide barrier height change ($\Delta\Phi_b/\Phi_{b0}$) in an n-channel MOSFET *vs.* charge injection (Q_{inj}) for substrate injection. (a) Negative and (b) positive I-V measurement.

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 (ΔA and ΔB) 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

$$\frac{\Delta A}{A_0} = -\frac{\Delta\Phi_b}{\Phi_{b0}} \quad [4]$$

and

$$\frac{\Delta B}{B_0} = \frac{3}{2}\frac{\Delta\Phi_b}{\Phi_{b0}} \quad [5]$$

where Φ_{b0} is the Φ_b 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 ΔE, ΔA, and ΔB

$$\ln\left(\frac{J}{J_0}\right) = \ln\left(1 + \frac{\Delta A}{A_0}\right) + 2\ln\left(1 + \frac{\Delta E}{E_0}\right) + \frac{B_0}{E_0}\,\frac{\frac{\Delta E}{E_0} - \frac{\Delta B}{B_0}}{1 + \frac{\Delta E}{E_0}} \quad [6]$$

Inserting Eq. 4 and 5 into Eq. 6, and if $\Delta E/E_0$ and $\Delta\Phi_b/\Phi_{b0}$ are small, one can obtain

$$\ln\left(\frac{J}{J_0}\right) \approx -\left(1 + \frac{3}{2}\frac{B_0}{E_0}\right)\frac{\Delta\Phi_b}{\Phi_{b0}} + \left(2 + \frac{B_0}{E_0}\right)\frac{\Delta E}{E_0} \quad [7]$$

As $(3/2)(B_0/E_0) \gg 1$, Eq. 7 can be also expressed approximately as

$$E_0 \ln\left(\frac{J}{J_0}\right) \approx -\left[\frac{3}{2}\left(\frac{\Delta\Phi_b}{\Phi_{b0}}\right)B_0 - 2\Delta E\right] + \frac{(B_0\Delta E)}{E_0} \quad [8]$$

Because B_0, ΔE, and $\Delta\Phi_b/\Phi_{b0}$ 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 ΔE and $\Delta\Phi_b/\Phi_{b0}$. 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 $\Delta\Phi_b/\Phi_{b0}$ *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 $\Delta\Phi_b/\Phi_{b0}$ *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 been seen in all these figures (note that $\Delta\Phi_b/\Phi_{b0}$ *vs.* Q_{inj} is plotted in log-log scale), the $\Delta\Phi_b/\Phi_{b0}$ follows

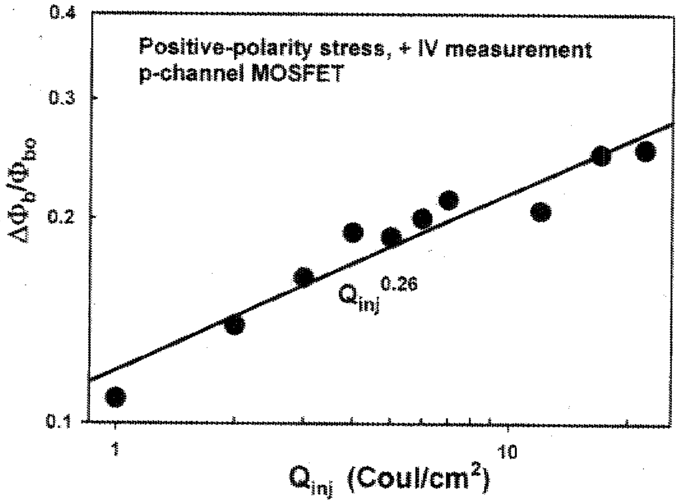

Figure 4. Oxide barrier height change ($\Delta\Phi_b/\Phi_{b0}$) in a p-channel MOSFET *vs.* charge injection (Q_{inj}) for positive-polarity stress and positive I-V measurement.

a sublinear power law, *i.e.*, $\Delta\Phi_b/\Phi_{b0} = AQ_{inj}^n$ 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 ΔE (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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