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A quantitative study of the relationship between the oxide charge trapping over the drain extension and the off-state drain leakage current

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In this letter, we report an approach to quantitative study of the relationship between the oxide charge trapping over the drain extension due to electrical stress and the off-state drain leakage current. It is found that positive charge trapping over the drain extension leads to a significant increase in the off-state drain current if the edge direct tunneling (EDT) is dominant in the drain current but in contrast, it leads to a reduction in the drain current if the band-to-band tunneling in the Si surface is dominant. A quantitative relationship between the charge trapping and the off-state drain leakage current in the EDT regime is established. From the measurement of the off-state current in the EDT regime, the charge trapping can be determined by using the approach developed in this study. © 2004 American Institute of Physics. [DOI: 10.1063/1.1810211]
thus a change in the EDT. The corresponding oxide voltage change can be described by $\Delta V_{ox} = Q_{ox}/C_{ox}$ where $Q_{ox}$ is the oxide charge trapping over the drain extension defined as the equivalent areal density at the Si/SiO2 interface, and $C_{ox}$ is the oxide capacitance per unit area. Based on the gate tunneling current model in Ref. 9 and taking into account the charge trapping, the gate tunneling current (i.e., the EDT) is found to be given by

$$I_g = A' \exp \left\{ \frac{20}{\phi_b} \left[ \frac{|V_{ox}| + Q_{ox}/C_{ox}}{0.6} \right] - 1 - \left( \frac{|V_{ox}| + Q_{ox}/C_{ox}}{\phi_b} \right) \right\} \times \exp \left[ -BT_{ox} \left( 1 - 1 - \frac{|V_{ox}| + Q_{ox}/C_{ox}}{\phi_b} \right)^{1.5} \right],$$

where $A' = A_{eff}(C_{ox}/V_{ox})^0.6$, $A = q^3/8\pi\hbar\phi_b$, and $B = 8\pi \sqrt{2m_{ox}^* e_b^3}/3hq$.

$V_{ox0}$ is the externally applied gate oxide voltage, $N$ is the carrier density, $V_g$ is the potential difference between the gate and drain, $A_{eff}$ is the area of the drain extension, $T_{ox}$ is gate oxide thickness, $\varepsilon_{ox} = 3.9\varepsilon_0$ ($\varepsilon_0 = 8.854 \times 10^{-12}$ F/cm) is dielectric constant of SiO2, $m_{ox} = m_0 / q$ is the carrier effective mass, $\phi_b = 0.6$ V is the oxide barrier height, $q$ is electronic charge, and $h$ is the Planck constant. If the off-state current is dominated by the EDT, the drain current $I_{off} = I_g$. In the following discussions, all are limited to this case, i.e., the off-state drain current in the EDT regime $I_{off} = I_g$. The off-state drain current calculated with Eq. (1) versus the charge trapping is shown in Fig. 2, and the calculation is also compared with the measurement result as shown in the figure.

Usually, $|V_{ox0}| \gg |\Delta V_{ox}| = |Q_{ox}/C_{ox}|$. Therefore, Eq. (1) can be approximately written as

$$\ln(I_{off}/I_{off0}) = aQ_{ox} + bQ_{ox}^2,$$  

where $I_{off0}$ is the off-state drain current before electrical stress (i.e., $Q_{ox} = 0$),

$$a = \frac{20|V_{ox0}|^0.6}{\phi_b^2 C_{ox}^0} \left[ 0.6(\phi_b - |V_{ox0}|) - 1 \right] - \frac{BT_{ox}}{\phi_b^0 |V_{ox0}| C_{ox}^0} \times \left[ 1.5(\phi_b - |V_{ox0}|)^{0.5} - \phi_b^{1.5} |V_{ox0}|^{0.5} + (\phi_b - |V_{ox0}|)^{1.5} \right],$$

$$b = -\frac{10}{\phi_b^{2.5} |V_{ox0}|^{0.4} C_{ox}^{2.5}} \left[ 0.96 + 0.24 |V_{ox0}| \phi_b - |V_{ox0}| \phi_b^{1.5} |V_{ox0}|^{0.5} + \phi_b^{1.5} (\phi_b - |V_{ox0}|)^{1.5} \right].$$

Therefore, from the measurement of the off-state drain current in the EDT regime, one can obtain the oxide charge trapping from Eq. (2).

To determine the $Q_{ox}$, one can measure the off-state drain leakage current $I_{off-m(i)}$ in the EDT regime at different oxide voltage $V_{ox0}(i)$ ($i = 1, 2, 3, \ldots, n$) where $n$ is the number

FIG. 1. (a) Typical $I-V$ characteristics for nMOSFET before electrical stress; (b) energy band diagram in the drain extension before and after positive charge trapping and the illumination of the EDT and BTBT; and (c) drain current change in the EDT and BTBT regimes after a 300 s electrical stress.

FIG. 2. Off-state drain current as a function of charge trapping. A linear relationship between the current and the charge trapping is observed for low charge trapping. The calculation shown in the inset indicates that a nonlinear relationship appears when $Q_{ox} \gg 2 \times 10^{13}$ cm$^{-2}$.
of the data points) before and after electrical stress and then fit the measurement data by minimizing the error function below

\[
F(Q_{ox}) = \sum_{i=1}^{n} \left[ \ln \left( \frac{I_{off-m}(i)}{I_{off-m}(i)} \right) - \ln \left( \frac{I_{off-cal}(i)}{I_{off-cal}(i)} \right) \right]^2
\]

\[
= \sum_{i=1}^{n} \left[ \ln \left( \frac{I_{off-m}(i)}{I_{off-m}(i)} \right) - a(i)Q_{ox} - b(i)Q_{ox}^2 \right]^2, \quad (3)
\]

where \(I_{off-cal}(i)\) is the off-state drain current calculated with Eq. (2). The \(Q_{ox}\) corresponding to the minimum \(F\) can be found from \(dF/dQ_{ox}=0\). We have found that the second-order contribution of the \(Q_{ox}\) [i.e., the term of \(b(i)Q_{ox}^2 \) in Eq. (3)] is negligible for actual charge trapping. For this case, the \(Q_{ox}\) can be easily calculated with

\[
Q_{ox} = \left\{ \sum_{i=1}^{n} a(i) \ln \left[ \frac{I_{off-m}(i)}{I_{off-m}(i)} \right] \right\} / \sum_{i=1}^{n} a^2(i). \quad (4)
\]

To check the correctness and accuracy of the above equations, we have calculated the \(I_{off}\) with Eq. (1) using the \(Q_{ox}\) values yielded from Eq. (4) and then compared the calculated \(I_{off}\) with the corresponding measurement data. As shown in Fig. 3, the agreement between the calculation and the measurement is excellent.

Figure 4(a) shows the increase in the \(I_{off}\) with stress time. From the measured \(I_{off}\), the oxide charge trapping is calculated with Eq. (4) for different stress time, and the result is shown in Fig. 4(b). As can be seen in Fig. 4(b), the dependence of the charge trapping on the stress time \((t)\) follows a power law, i.e., \(Q_{ox} \propto t^n\) with the exponential factor \(n=0.25\). Similar power-law behaviors have been reported in literature.\(^5\) The exponent of 0.25 suggests that the charge trapping could be related to diffusion–limited electrochemical reactions.\(^6,7\) On the other hand, after the stress-time dependence of the charge trapping is obtained, the stress-time dependence of the off-state drain current can be also calculated with Eq. (1). The calculated stress-time dependence of the increase of the \(I_{off}\) is shown in Fig. 4(a).

In conclusion, we have developed an approach to quantitative study on the influence of the oxide charge trapping over the drain extension caused by electrical stress on the off-state drain leakage current. It is shown that positive charge trapping over the drain extension leads to a significant increase in the off-state drain current if the EDT is dominant in the drain current. The quantitative relationship between the charge trapping and the off-state drain current in the EDT regime is obtained. By measuring the off-state drain current in the EDT regime and using the formula developed in this work, the charge trapping is determined quantitatively.

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