Depth localization of positive charge trapped in silicon oxynitride field effect transistors after positive and negative gate bias temperature stress

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Positive charge trapped in the SiO(N) gate dielectric of deep-submicron p-channel metal-oxide-semiconductor field-effect transistors is observed after both negative and positive gate bias temperature stress. Emission of elementary trapped charges is demonstrated and analyzed through the quantized threshold voltage transients observed after stress. The magnitude distribution of the threshold voltage steps is used to estimate the depth of the traps in the gate dielectric to be about 0.5 nm from the injecting silicon-dielectric interface in both cases. © 2011 American Institute of Physics. [doi:10.1063/1.3586780]

The negative bias temperature instability (NBTI) is one of the most serious reliability issues in p-channel metal-oxide-semiconductor field effect devices (pMOSFETs).1 NBTI manifests itself as a negative threshold voltage shift (ΔV_{TH}) produced after the application of a negative gate bias at elevated temperature in pMOSFETs. This effect is due to the trapping of positive charge injected from the silicon substrate inversion layer.2 In polysilicon pMOSFETs, negative ΔV_{TH} is also observed after positive gate bias stress.3,4 We argue that this observation is in fact produced by the same process flow except for the SiO\textsubscript{2} gate after stress. Emission of elementary trapped charges is demonstrated and analyzed through the quantized threshold voltage transients observed after stress. The discrete ΔV_{TH} drops are single hole emission events from individual traps.5 The number of discrete ΔV_{TH} drops per device follows a Poisson distribution (not shown). The large step heights are caused by the nonuniform inversion charge caused by the random dopant fluctuations in the pMOSFET channel. This inversion charge can be modified by the capture and emission of individual oxide traps, thus varying the drain current I_{D}.6 Taking the I_{D}-V_{G} curve of the fresh device as a reference, the changes in the drain current I_{D} can be transformed into the ΔV_{TH} shift.

Comparing Figs. 1(a) and 1(b), we note that both the total ΔV_{TH} shift and the magnitude of the step heights are lower for the case of positive gate stress. This becomes more evident in Fig. 2, where the averaged relaxation traces of 74 devices after positive and negative stress are plotted together. The resulting curves resemble the continuous curves obtained in large gate area devices for both negative and positive stress conditions (not shown here). This corroborates the assumption that the relaxation transients obtained on large devices are the result of the emission of multiple holes trapped in the gate dielectric.

The complementary cumulative distribution functions (CCDFs) of the step heights from Fig. 1 displayed in Fig. 3 further demonstrate that larger step heights are seen after negative stress. Both CCDFs follow an exponential distribution.10

\[ \text{CCDF}(\Delta V_{TH}, \eta) = \exp\left( -\frac{\Delta V_{TH}}{\eta} \right), \] (1)

where \( \eta = \langle\Delta V_{TH}\rangle \) is the average step height for a single discharge. The normalizing constant for both CCDFs plotted in Fig. 3 \( N_{i} \) was \( \sim 150 \) for both polarities. This constant...
represents the total number of the emitted holes per 74 devices, that is about two emitted holes per device. The close value obtained for \( N_t \) under both conditions indicates that the number of positive charge trapped during both stress conditions was roughly the same. On the other hand, \( \eta \) is equal to \(-4.4\) and \(-1.5\) mV for the negatively and positively stressed devices, respectively (Table I). We interpret this disparity as the consequence of the different average distance \( \langle x_0 \rangle \) (i.e., the depth) of the trapped holes in the oxide from the polysilicon gate after negative and positive stress conditions, as sketched in Fig. 4. This discrepancy allows us to estimate the average positive charge position when two simple assumptions are made. First, the average distance \( \langle x_T \rangle \) from the injection interface (the substrate for the negative stress and the polysilicon for the positive stress) to the trapped holes is equal for both stress polarities. This assumption will be correct provided that the tunneling probabilities to both interfaces are comparable. The tunneling probability does not depend strongly on the electronic barrier between Si and SiO(N) but rather on the vibrational barriers. Since the absolute value of the electric field is identical in both cases and the defect properties at the two interfaces are analogous, the tunneling probabilities can be expected to be practically identical. Second, the average threshold voltage shift produced by the single discharge \( \eta(\Delta V_{TH}) \) is proportional to the charge centroid \( \langle x_T \rangle \) from the polysilicon for negative and positive stress conditions, respectively, i.e.,

\[
\eta(\Delta V_{TH} < 0) \propto (\langle x_0 \rangle - \langle x_T \rangle)
\]

and

\[
\eta(\Delta V_{TH} > 0) \propto \langle x_T \rangle.
\]

The ratio between the average single discharge \( \eta \) for negative and positive stress readily yields the expected \( \langle x_T \rangle \) as

\[
\langle x_T \rangle = \frac{\eta(\Delta V_{TH} > 0)}{\eta(\Delta V_{TH} < 0) + \eta(\Delta V_{TH} > 0)}.
\]

### Table I. Average step heights \( x_T \) produced by the emission of a single positive charge after negative and positive bias stress conditions for the two stacks studied in this experiment.

<table>
<thead>
<tr>
<th>Electric field (MV/cm)</th>
<th>( t_{\text{stress}} = 2.3 \text{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{ox}} = -7 \text{MV/cm} )</td>
<td>(-4.4)</td>
</tr>
<tr>
<td>( E_{\text{ox}} = +7 \text{MV/cm} )</td>
<td>(-1.5)</td>
</tr>
</tbody>
</table>
Substituting the values of \( \eta \) (see Table I) for the devices with 1.86 nm SiO(N) in Eq. (4), we obtain the average depth of the trapped positive charge \( \langle x_T \rangle \) equal to 0.47 nm.

The experiment was repeated on a wafer with a thinner SiO(N) layer \( t_{SiON} = 1.42 \text{ nm} \) and slightly larger drawn gate size \( L \times W = 100 \times 100 \text{ nm}^2 \). The oxide electric field and the stress time were identical for positive and negative stress, resulting again in approximately the same number of defects, indicated by similar normalizing factors for both CCDFs. In this case, the average step heights \( \eta \) were \(-1.5\) and \(-0.8\) mV for the negative and the positive stress, respectively (Table I). Lower \( \eta \) values but higher normalizing factor for the CCDFs are obtained as expected for larger area devices \( L \times W = 100 \times 100 \text{ nm}^2 \), corresponding to a larger total number of defects but with a smaller average impact in the total threshold shift.\(^9\) The trap position \( \langle x_T \rangle \) obtained from these values via Eq. (4) is 0.49 nm.

The similar \( \langle x_T \rangle \) values obtained from both the 1.86 nm and 1.46 nm SiO(N) pMOSFET devices (see Table I) lead us to conclude that under identical stress conditions (the oxide electric field and the stress time), the average trap position of the injected holes is equal.

In conclusion, the average depth position of positive trapped charge in poly-Si/SiO(N)/p-Si FETs has been determined by means of studying individual hole emission events after positive and negative stress.

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