Extraction of nitride trap density from stress induced leakage current in silicon-oxide-nitride-oxide-silicon flash memory
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Extraction of nitride trap density from stress induced leakage current in silicon-oxide-nitride-oxide-silicon flash memory

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The authors propose a technique to extract a silicon nitride trap density from stress induced leakage current in a polycrystalline silicon-oxide-nitride-oxide-silicon flash memory cell. An analytical model based on the Frenkel-Poole emission is developed to correlate a nitride trap density with stress induced leakage current. The extracted nitride trap density is $7.0 \times 10^{15}$ cm$^{-2}$ eV$^{-1}$. They find that nitride trapped charges have a rather uniform distribution in an energy range of measurement ($\approx 0.2$ eV). © 2006 American Institute of Physics. [DOI: 10.1063/1.2360180]

Polycrystalline silicon-oxide-nitride-oxide-silicon (SONOS) flash memories have received much interest in recent years for their simpler fabrication process and better scalability as compared to conventional floating gate flash memory. For SONOS cells, programmed charges are stored in silicon nitride traps. The cell programming and retention characteristics are intimately related to nitride trap characteristics. Much research effort with respect to silicon nitride process optimization has been conducted to improve nitride trap properties. However, nitride trap characterization techniques are still very limited at present. Lundström and Svensson estimated a nitride trap density with a direct tunneling model. Paulsen et al. employed a low-frequency (<1 kHz) charge pumping technique to separate nitride traps from interfacial oxide traps by a difference in their time constants. Later, they extracted a nitride trap density from reverse modeling of threshold voltage ($V_t$) retention loss by combining trap-to-band tunneling and thermal excitation of trapped electrons in a nitride. All the above methods, however, are restricted to ultrathin bottom oxides (1.5–2.5 nm). For today’s SONOS cells, for example, nitride-read-only-memory (NROM) (Ref. 7) or Nitride-based multiple bits/cell (Nbit) (Ref. 8) technology, a thicker bottom oxide is usually employed to improve data retention. No appropriate nitride trap characterization methods are available for these cells.

In this work, we observe a high-voltage stress induced gate leakage current in a large area SONOS capacitor. An analytical model to extract a nitride trap density from the stress induced leakage current is developed. The effects of programming window ($\Delta V_t$) and stress condition on the extraction result are evaluated. The nitride trap energy distribution is also profiled.

The SONOS capacitors used in this work have a 9 nm top oxide, a 6 nm silicon nitride, and a 5 nm bottom oxide. The capacitor area is $500 \times 500 \mu$m$^2$. Uniform Fowler-Nordheim (FN) injection is employed for programming. The measured program-state gate leakage current versus retention time before and after a FN stress is shown in Fig. 1(a). The FN stress is performed at $V_g = -20$ V for 1500 s. The program $V_t$ window is 3 V. The corresponding $V_t$ retention loss is shown in Fig. 1(b). A significant stress induced leakage current (SILC) is observed in Fig. 1(a). Unlike in a metal oxide semiconductor capacitor, the SILC in a SONOS exhibits a unique two-stage time dependence. In the first stage, the SILC exhibits a dc-like characteristic and in the second stage it follows a $t^\alpha$ time dependence. Our numerical simulation has shown that the first stage leakage current is limited by stress created oxide traps and the second stage is determined by the Frenkel-Poole (FP) emission of nitride trapped electrons. According to the FP emission model, the nitride trapped charge emission time is

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{(a) Measured gate leakage current in a large area SONOS (500 \times 500 \mu m$^2$) at $V_g = 0$ V. The stress condition is $V_g = -20$ V for 1500 s. Both devices are programed to an identical threshold voltage window of 3 V. (b) Corresponding $V_t$ retention loss for the two samples.}
\end{figure}
where \( A^* \) is the Richardson constant, \( \phi \) is the nitride trap energy measured from the conduction band edge, \( E \) is the electric field, \( \tau' \) is the proportionality constant, and other variables have their usual definitions. In the FP emission limited condition (second stage), the electron occupation factor \( (f) \) of a nitride trap state with an energy \( \phi \) has a retention time dependence as follows:

\[
f(\phi) = \exp\left(-t/\tau_c(\phi)\right) = \exp\left(-t/\tau' \exp(-\phi/kT)\right).
\]

Because the above double exponential changes abruptly from 0 to 1 around \( \phi_f = (kT)\ln(t/\tau') \), \( f(\phi) \) can be approximated by a step function at \( \phi = \phi_f \) and thus \( \phi_f \) is referred to as the FP emission front hereafter. This approximation translates into a “clear-cut” picture; at a certain time \( t \), trap states above the emission front \( \phi_f \) are completely emptied while the states below \( \phi_f \) are occupied by electrons. The FP emission front moves downward in SiN band gap with a speed of \( d\phi_f/dt = kT/t \), or 2.3kT/decade of time. The nitride charge leakage current in the second stage therefore can be expressed as

\[
I_s = AqN_s(\phi_f)d\phi_f/dt = AqN_s(\phi_f)kT/t
\]

and the nitride trap density can be extracted as

\[
N_s(\phi_f) = I_s/tAqkT.
\]

Since the emission front stays almost unchanged in the first stage \( (\phi_f = \phi_0) \) and begins to move at the onset time \( t_{on} \) of the second stage with a constant speed in a log\( (t) \) scale, the relationship between \( \phi_f \) and retention time \( t \) is readily obtained,

\[
\phi_f = \phi_0 + kT \ln(t/t_{on}),
\]

where \( \phi_0 \) is the emission front in the first stage and is determined by the total amount of programed charges. From our numerical simulation, \( \phi_0 \) is estimated to be 0.8 eV for the present SONOS structure and programming window. From Eqs. (3) and (4), the nitride trap density is characterized, as shown in Fig. 2. The solid line is directly from the SILC [Fig. 1(a)] and the dashed line is extrapolated from the \( V_r \) shift [Fig. 1(b)]. Notably, Fig. 2 reveals that the trapped charges have a rather uniform distribution over an energy range of measurement (~0.2 eV).

To further verify our nitride trap profiling technique, we change the FN stress condition and programming window. Figure 3 shows the SILC for two different FN stresses. The two samples have the same programming window and thus the same \( \phi_0 \). It can be shown that the effective time for nitride trapped charges at the emission front to escape from the ONO film

\[
\tau_{eff} = \frac{\tau_c(\phi_f) + \tau_c(\phi_0)}{\tau_c(\phi_f) + \tau_{ox}} = \frac{\tau_c(\phi_f) + \tau_{ox}}{\tau_c(\phi_0) + \tau_{ox}},
\]

where \( \tau_c(\phi_f) \) and \( \tau_c(\phi_0) \) represent the electron emission time and capture time between the emission front and the nitride conduction band. \( \tau_{ox} \) is the conduction band electron tunneling time via stress induced oxide traps. The lightly stressed sample (B) has a lower first-stage dc leakage because of less oxide trap creation and thus a longer \( \tau_{ox} \). It is worth pointing out that the SILC in the two samples (A and B) converges in the second stage. The reason is that the \( \phi_f \) of the two samples at a certain time in the second stage is only shifted by \( kT \ln(t_{on}(B)/t_{on}(A)) \sim 0.06 \text{ eV} \). As mentioned earlier, the nitride trap density \( N_s \) is almost a constant in the measurement range. The leakage current, which is proportional to \( N_s \), is therefore nearly the same in the second stage regardless of stress conditions.

In addition, the SILC for different program windows is shown in Fig. 4. The program window is 3 V for sample A and is 2.5 V for sample C. Sample A has a smaller \( \phi_0 \) for more programed charges. According to the Shockley-Read-
Hall theory, $\tau_e/\tau_c \propto \exp(\phi/kT)$ and the difference in $\phi_0$ between samples A and C can be estimated from the ratio of the SILC in the first stage, i.e.,

$$\text{SILC(first stage)} \propto 1/\tau_{\text{eff}} \propto \exp(-\phi_0/kT)$$

and

$$\phi_0(A) - \phi_0(C) = -kT \ln(\text{SILC}(A)/\text{SILC}(C)). \quad (6)$$

The $\phi_0$ difference is still small. Consequently, samples A and C have almost the same leakage current in the second stage because $N_t(\phi)$ can be considered as a constant for such small $\phi_0$ difference. The extracted nitride trap density from samples A–C is listed in Table I. The extracted result is in reasonably good agreement without regard to stress condition and programming window.

In summary, a simple and reliable nitride trap profiling technique for a thicker bottom oxide SONOS is developed. We find that a SILC in a SONOS exhibits a distinguished two-stage feature. The nearly $1/t$ dependence in the second stage suggests that the nitride traps have a uniform energy distribution. The extracted nitride trap density is around $7.0 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_t$ (cm$^{-2}$ eV$^{-1}$)</th>
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<tbody>
<tr>
<td>A</td>
<td>$7.1 \times 10^{12}$</td>
</tr>
<tr>
<td>B</td>
<td>$6.3 \times 10^{12}$</td>
</tr>
<tr>
<td>C</td>
<td>$6.2 \times 10^{12}$</td>
</tr>
</tbody>
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