Conduction modeling of thick nitride/oxide dielectrics

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Current-voltage measurements demonstrate that conduction current in thick nitride is the sum of Ohmic and Frenkel–Poole (F–P) currents \( J^{\text{NIT}} = J^{\text{OHMIC}} + J^{\text{FP}} \) and in thick oxide is a low-level Ohmic current with weak temperature dependence \( J^{\text{OX}} \). Both conduction currents play a dominant role in threshold voltage instabilities (\( \Delta V_{T} \)) in double-layer nitride/oxide structures [1, 2]. The presented conduction model is based on Laplace equations which takes Ohmic and F–P currents in dielectrics into account. The equations are numerically solved with finite-element method under Dirichlet boundary conditions using the SGFramework simulator [3].

In the present work a multi–dielectric capacitor consists of the following layers: metal 1 plate (metal gate), Si\(_3\)N\(_4\) film, Si\(_3\)N\(_4\)/BPTEOS interface, BPTEOS film, BPTEOS/LOCOS interface, LOCOS film, and metal 2 plate (silicon substrate with Si\(_3\)N\(_4\) (outer) and oxide (inner) dielectric [2]. The electric neutrality of the dielectrics may initially be assumed if there are no free charges in the capacitor (\( V_{FB} = 0 \)) before the VG is turned on. To define the electric field (\( E_{0} \)) and potential (\( V_{0} \)) in the capacitor we should solve the Laplace equation for each dielectric layer:

\[
\frac{\partial^{2} V_{X}}{\partial x^{2}} = 0; \quad \text{(1)}
\]

Since \( D_{X} = \varepsilon_{0} \varepsilon_{X} E_{X} \) and \( D_{X1} = D_{X2} \) we can write:

\[
\varepsilon_{1} \cdot E_{X1} = \varepsilon_{2} \cdot E_{X2}; \quad \text{(2)}
\]

In the equations it is assumed that \( E_{X} \) and \( D_{X} \) are continuous at the boundaries. For the numerical calculations in the case of one-dimensional Laplace equations, we can re-write (1) and (2) in a finite–difference (FD) form [3]:

\[
\varepsilon_{1} \frac{V_{X+1} - 2V_{X} + V_{X-1}}{\Delta x^{2}} = 0; \quad \text{(3)}
\]

Knowing \( E_{X} \) and \( V_{x} \) we can calculate the conduction currents in the corresponding dielectric.

F–P conduction current in thick nitride can be expressed in a FD form:

\[
J_{F-P} = C_{F-P} \cdot \left| \text{grad} V_{X} \right| \cdot \exp\left( -\frac{q}{\pi \varepsilon_{0} \varepsilon_{X} \beta} \right) \left| \text{grad} V_{X} \right| / k^{*} T; \quad \text{(5)}
\]

where \( \beta = \frac{q}{\pi \varepsilon_{0} \varepsilon_{X} \beta} \) is the F–P emission coefficient.

Ohmic conduction current in thick nitride in a FD form:

\[
J_{\text{OHMIC}}^{\text{NIT}} = C_{\text{OHMIC}}^{\text{NIT}} \left| \text{grad} V_{X} \right| \exp\left( \frac{E_{\text{OHMIC}}^{\text{NIT}}}{k^{*} T} \right); \quad \text{(6)}
\]

Ohmic conduction current in thick oxide in a FD form:

\[
J_{\text{OHMIC}}^{\text{OX}} = C_{\text{OHMIC}}^{\text{OX}} \left| \text{grad} V_{X} \right| \exp\left( \frac{E_{\text{OHMIC}}^{\text{OX}}}{k^{*} T} \right);
\]

If the current densities \( J^{\text{NIT}} \) and \( J^{\text{OX}} \) are not equal, the injected charge density (\( Q \)) accumulates according to the following equation:

\[
J^{\text{NIT}} - J^{\text{OX}} = C^{\text{NIT}} \frac{\partial V_{X}}{\partial x} - C^{\text{OX}} \frac{\partial V_{X}}{\partial x} = C^{\text{NIT}} \Delta V_{T}; \quad \text{(8)}
\]

where \( C^{\text{NIT}} \) is the nitride capacitance per unit area and \( \Delta V_{T} \) is the stress time. From (8) the voltage shift \( \Delta V_{T} \) can be calculated:

\[
\Delta V_{T} = \frac{1}{C^{\text{NIT}}} \left[ \int_{0}^{\inf} (J^{\text{NIT}} - J^{\text{OX}}) dt \right] \approx \frac{d_{\text{NIT}}}{\varepsilon_{o} E_{\text{NIT}}} \left( J^{\text{NIT}} - J^{\text{OX}} \right) \Delta t \approx \frac{d_{\text{NIT}}}{\varepsilon_{o} E_{\text{NIT}}} \Delta V_{T}^{\text{MAX}}; \quad \text{(9)}
\]

The maximum \( \Delta V_{T}^{\text{MAX}} \) has already been estimated [2]:

\[
\Delta V_{T}^{\text{MAX}} = V_{G} - V_{0}^{\text{OX}} = \frac{V_{G}}{1 + \left| \frac{d_{\text{NIT}}}{\varepsilon_{o} E_{\text{NIT}}} \right|}; \quad \text{(10)}
\]

We can also compute the stress saturation time \( \Delta t_{\text{SAT}} \) necessary to reach the maximum \( \Delta V_{T}^{\text{MAX}} \) from the equation [8]:

\[
\Delta t_{\text{SAT}} = \frac{C^{\text{NIT}} \Delta V_{T}^{\text{MAX}}}{J^{\text{NIT}} - J^{\text{OX}}} = \frac{\varepsilon_{0} E_{\text{NIT}} \Delta V_{T}^{\text{MAX}}}{d_{\text{NIT}} \left( J^{\text{NIT}} - J^{\text{OX}} \right)} = \frac{\varepsilon_{0} E_{\text{NIT}}}{d_{\text{NIT}} \left( J^{\text{NIT}} - J^{\text{OX}} \right)}; \quad \text{(11)}
\]

The simulation program calculates \( \Delta t_{\text{SAT}} \) from (11) and compares that value with the user input for \( \Delta t_{\text{STRESS}} \). If \( \Delta t_{\text{STRESS}} \geq \Delta t_{\text{SAT}} \) than \( \Delta t_{\text{SAT}} \) value is used instead of \( \Delta t_{\text{STRESS}} \) to predict the \( \Delta V_{T} \) voltage instabilities. Otherwise the \( \Delta V_{T} \) value is calculated straightforward from (9).

In the described model it is assumed that the injected charge is stored at the nitride/oxide interface, however, a presumably broader charge distribution throughout the nitride (due to bulk–limited F–P trapping) may introduce some discrepancy with experimental data.

Jersey, 1997).