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 $J^{NIT} = J^{NIT}_{OHMIC} + J^{NIT}_{FP}$ and in thick oxide is a low-level Ohmic current with weak temperature dependence $J^{OX} = J^{OX}_{OHMIC}$. Both conduction currents play a dominant role in threshold voltage instabilities (ΔV_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_3N_4 film, Si_3N_4/BPTEOS interface, BPTEOS film, BPTEOS/LOCOS interface, LOCOS film, and metal 2 plate (silicon substrate with $\Psi_S=\Phi_{MS}=0$). The electric charge is injected and transferred during the gate stress V_G by difference in conduction currents between the Si_3N_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 V_G is turned on. To define the electric field (E_X) and potential (V_X) in the capacitor we should solve the Laplace equation for each dielectric layer:

$$\frac{\partial^2 V_X}{\partial x^2} = 0\,; \qquad \{1\}$$

Since $D_X = \varepsilon_0 * \varepsilon * E_X$ and $D_{X1} = D_{X2}$ we can write:

$$\varepsilon_1 * E_{X1} = \varepsilon_2 * E_{X2}\,; \qquad \{2\}$$

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]:

$$\frac{V_X[i-1] - 2*V_X[i] + V_X[i+1]}{(\Delta x)^2} = 0\,; \qquad \{3\}$$

$$\varepsilon_1 * \frac{V_X[i] - V_X[i-1]}{\Delta x} = \varepsilon_2 * \frac{V_X[i+1] - V_X[i]}{\Delta x}\,; \qquad \{4\}$$

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:

$$J_{FP}[i] = C_{FP} * \left|gradV_X[i]\right| * \exp\left(-\frac{\Phi_t - \beta * \sqrt{\left|gradV_X[i]\right|}}{k*T}\right); \qquad \{5\}$$

where $\beta = \sqrt{\dfrac{q}{\pi * \varepsilon_0 * \varepsilon_D}}$ is the F–P emission coefficient.

Ohmic conduction current in thick nitride in a FD form:

$$J^{NIT}_{OHMIC}[i] = C^{NIT}_{OHMIC} * \left|gradV_X[i]\right| * \exp\left(-\frac{E^A_{OHMIC}}{k*T}\right); \qquad \{6\}$$

Ohmic conduction current in thick oxide in a FD form:

$$J^{OX}_{OHMIC}[i] = C^{OX}_{OHMIC} * \left|gradV_X[i]\right|\,; \qquad \{7\}$$

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

$$J^{NIT} - J^{OX} = \frac{\partial Q_S(t)}{\partial t} = C^{NIT} * \frac{\partial V_T(t)}{\partial t} \approx C^{NIT} * \frac{\Delta V_T}{\Delta t_{STRESS}}\,; \qquad \{8\}$$

where C^{NIT} is the nitride capacitance per unit area and Δt_{STRESS} is the stress time. From {8} the voltage shift ΔV_T can be calculated:

$$\Delta V_T = \frac{1}{C^{NIT}} * \int_0^{t_{STRESS}} (J^{NIT} - J^{OX})dt = \frac{d_{NIT}}{\varepsilon_0 \varepsilon_{NIT}} * \int_0^{t_{STRESS}} (J^{NIT} - J^{OX})dt \approx$$

$$\approx \frac{d_{NIT}}{\varepsilon_0 \varepsilon_{NIT}} * (J^{NIT} - J^{OX}) * \Delta t_{STRESS}\,; \qquad \{9\}$$

The maximum ΔV_T^{MAX} has already been estimated [2]:

$$\Delta V_T^{MAX} = V_{OX} - V'_{OX} = -\frac{V_G}{1 + \dfrac{1}{\left(\dfrac{\varepsilon_{NIT}}{\varepsilon_{ox}} * \dfrac{d_{NIT}}{d_{OX}}\right)}}\,; \qquad \{10\}$$

We can also compute the stress saturation time Δt_{SAT} necessary to reach the maximum ΔV_T^{MAX} from the equation {8}:

$$\left|\Delta t_{SAT}\right| = \frac{C^{NIT} * \Delta V_T^{MAX}}{J^{NIT} - J^{OX}} = \frac{\varepsilon_0 * \varepsilon_{NIT} * \Delta V_T^{MAX}}{d_{NIT} * (J^{NIT} - J^{OX})} =$$

$$= \frac{\varepsilon_0 * \varepsilon_{NIT}}{d_{NIT} * (J^{NIT} - J^{OX})} * \frac{V_G}{1 + \dfrac{1}{\left(\dfrac{\varepsilon_{NIT}}{\varepsilon_{ox}} * \dfrac{d_{NIT}}{d_{OX}}\right)}}\,; \qquad \{11\}$$

The simulation program calculates Δt_{SAT} from {11} and compares that value with the user input for Δt_{STRESS}. If $\Delta t_{STRESS} \geq \Delta t_{SAT}$ than Δt_{SAT} value is used instead of Δt_{STRESS} to predict the ΔV_T voltage instabilities. Otherwise the ΔV_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.

[1] G. Barbottin and A.V. Vapaille, *Instabilities in Silicon Devices*, edited by P. Gentil (Elsevier Science, Amsterdam, 1989), Chap. 16.

[2] S. Evseev, A. Cacciato, and J. van der Pol, *Conduction-related voltage instabilities in double-layer dielectric films*, J. Appl. Phys. Vol. 91 (9), 1 May (2002), pp. 6206-6208.

[3] K. Kramer and W. Hitchon, *Semiconductor Devices*, A Simulation Approach, (Prentice Hall, New

Jersey, 1997).