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Nonlocal Oxide Injection Models

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Abstract

Three models for hot carrier injection into the gate oxide layer of a MOSFET are examined and compared with gate current measurement.

1. Introduction

In order to develop models for the simulation of hot carrier degradation of deep-sub-μm MOSFET's, the oxide injection of hot carriers and the transport of the injected carriers inside the gate oxide layer are investigated. Considering the sharply peaked electric field near drain, it is clear that a model for the injection of hot carriers, that relies purely on local values of electric field and carrier concentration, is not appropriate. In section 2 we present three models to calculate the injected current.

To describe the oxide transport of injected carriers a 2-D continuity equation is solved on the whole oxide bulk, resulting in oxide current densities, which allow to calculate gate currents and are the necessary input for oxide trapping calculation.

The injection models and the oxide transport approach were implemented into the device simulator MINIMOS. Gate current simulation results for all injection models are compared with experimental data for the case of a 0.9 μm MOSFET with 10 nm oxide thickness and purely As-doped drain junctions.

2. Models

Model I is based on the nonlocal ballistic lucky electron model introduced by Meinerzhagen for the calculation of oxide injection in MOSFETs [1]. In his work the oxide injection current is given by

$$j_{inj}(x_0) = A\, n[x(d)]\, v_{sat} \cos(\theta) \exp\left(-\frac{d}{\lambda}\right) \exp\left(-\frac{d_{ii}}{\lambda_{ii}}\right) \qquad (1)$$

where x_0 is the injection point, A is a constant, v_{sat} the saturation velocity, $x(d)$ that point on the electric field line path ending at the interface point x_0 with $\Psi(x(d)) = \Psi(x_0) - \Phi/q$ (for electrons), d the length of the path between $x(d)$ and x_0, λ the inelastic mean free path, λ_{ii} the mean free path for impact ionization scattering events, d_{ii} the path length between x_0 and $x(d_{ii})$ with $\Psi(x(d_{ii})) - \Psi(x(d)) = \Phi_{ii}/q$,[1] and θ the angle between the electric field vector and the vector normal to the Si/SiO$_2$–interface.

The basic idea of Model II is to integrate contributions from all over the semiconductor to the injected current at the respective oxide interface point. The general form of this injection formula is given by

$$j_{inj}\,(x_0) = \frac{A}{2\lambda} \int_{-\pi/2}^{\pi/2} d\phi\, \cos\phi \int_0^{\infty} dr\, \exp\Bigl(-\frac{r}{\lambda}\Bigr)\, |j(r,\phi)|\, \exp\Bigl(-\frac{\Phi - q\Delta\Psi}{qE_{\|}(r,\phi)\lambda'}\Bigr) \qquad (2)$$

where r is the distance between x_0 and the integration point (r, ϕ), and ϕ the angle between the connection line x_0 – (r, ϕ) and the interface normal. A is a proportionality constant , λ the inelastic mean free path, $j(r, \phi)$ the current density at the integration point in the semiconductor, $\Delta\Psi = \Psi(x_0) - \Psi(r, \phi)$ is used for the difference in electrostatic potential between integration and interface point. λ' is assumed to be smaller than λ, as it is used to estimate the "high energy temperature" ($k_B T_{high} := qE_{\|}\lambda'$).

In Model III the injected current is given by:

$$j_{inj}(x_0) \;=\; B\, v_{inj}^0\, \lambda_{inj}\, \frac{\partial}{\partial n}\Bigl[\int_V \frac{d^2x'}{\lambda^2}\, G(\boldsymbol{x}_0, \boldsymbol{x}')\, n(\boldsymbol{x}')\, \exp\Bigl(-\frac{\Phi - q\,\Delta\Psi}{qF\lambda}\, s(F)\Bigr)\Bigr] \quad (3)$$

where B is a constant, v_{inj}^0 is the particle velocitiy, λ_{inj} the mean free path at $\epsilon = \Phi$ respectively, the derivative is with respect to the interface normal, $k = \sqrt{3}\,(\lambda\lambda_{op})^{-1/2}$, and λ and λ_{op} are the total and the optical mean free path, $n(\boldsymbol{x}')$ is the particle density, F is the driving force and s is a parameter to determine the high energy temperature of the distribution by solving a transcendental equation [2]. The propagator $G(\boldsymbol{x}_0, \boldsymbol{x}')$ essentially varies exponentially with $-k\,|\boldsymbol{x}_0 - \boldsymbol{x}'|$, its detailed form is given in [3]. Note that the expression in the square brackets in equation 3 is essentially the product of the density of states and the isotropic part of the distribution function f_0.

For the threshold energy Φ, barrier lowering is taken into account according to [4].

3. Results and Discussion

A distinct difference between the results of Model I and Model II is found for values of U_G below the applied drain voltage U_D (see fig. 1 and 2). The reason is that behind the pinch off, where the maximum lateral electric field is found, there is no electric field component driving electrons into the oxide, causing a sharper decline of the injected current in the ballistic lucky electron model (Model I).

A comparison of measurement and simulation for Model III can be found in figure 3. Figure 4 shows simulation results of Model II and Model III of the gate current at 5.5V drain voltage for the full gate voltage range, together with the experimental data. For low gate voltage, also "positive" (i. e. hole) gate currents are predicted (still below the measurement limit of the equipment used for the gate current measurement). The bias region and the order of magnitude of this gate current, which is due to hot hole injection, is in good qualitative agreement with literature data [5].

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[1] Φ_{ii} is the threshold energy for impact ionization $\approx 1.5\,$eV

In Figures 5a and 5b the distribution of injected current along the Si/SiO$_2$–interface is shown for $V_D = 5.5V$, $V_G = 6V$. The slight shift of the peak injection current relative to the peak of the lateral electric field is due to the non-local nature of the injection models used.

4. Acknowledgment

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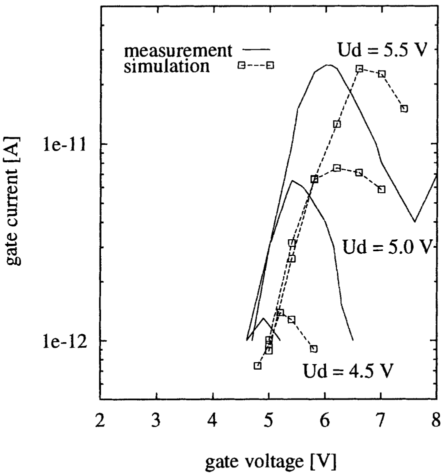

Figure 1: Gate current as a function of gate voltage for 3 different drain voltages U_D. Comparison of measurement (solid lines) and simulation using model I (dashed lines).

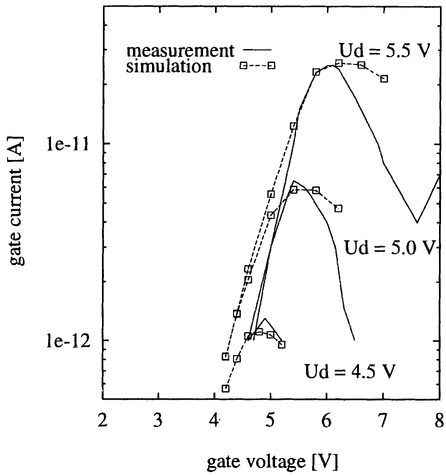

Figure 2: Gate current as a function of gate voltage for 3 different drain voltages U_D. Comparison of measurement (solid lines) and simulation using model II (dashed lines).

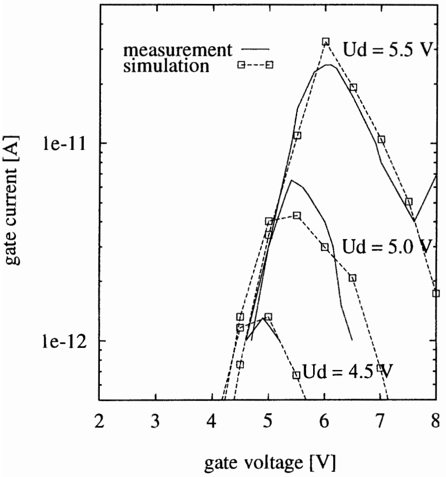

Figure 3: Gate current as a function of gate voltage for 3 different drain voltages U_D. Comparison of measurement (solid lines) and simulation using model III (dashed lines).

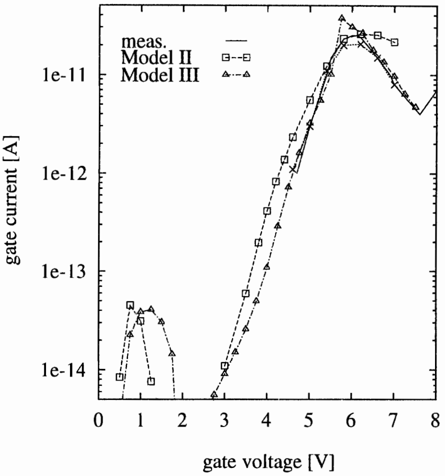

Figure 4: Gate current as a function of gate voltage for $U_D = 5.5V$. For $0 \leq U_G \leq 2$ the current is positive. Comparison of measurement (solid line) and simulation using model II (dashed line) and model III (dashed-dotted line).

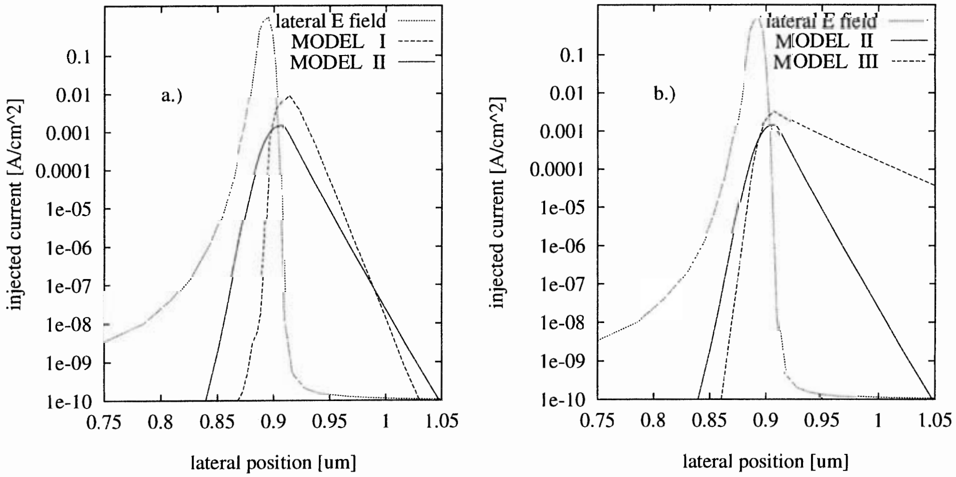

Figure 5: Injected current for the different models vs. lateral position for $U_G = 6V, U_D = 5.5V$. The gate edge is located at 0.9 μm. The electric field is plotted linearly with a maximum of $4.55 \cdot 10^5 V/cm^2$.