Abstract

Hot electron transport in MOS transistors is investigated by means of coupled silicon/oxide Monte Carlo (MC) simulation. First, a new MC simulator able to handle self-consistently different materials is developed. Then, impact of oxide transport on the gate current \( I_G \) is analyzed comparing measurements and simulations. Different injection models are also compared. It is shown that oxide transport plays an important role on \( I_G \) when the gate voltage is below the drain voltage \( V_{GS} < V_{DS} \). In this condition, coupled silicon/oxide simulation is needed to quantitatively assess \( I_G \). It is also shown that oxide scattering in the image force potential well does not significantly reduce \( I_G \).

1. Introduction

Although the continuous reduction of physical dimensions and applied voltage will make MOS transistors work in the direct tunnel regime [1], there is still a large class of MOS devices with oxide thickness \( t_{ox} \) larger than 3nm in which the gate current \( I_G \) is due to hot electrons. These electrons are mostly emitted over the energy barrier at the silicon/oxide interface and travel across the oxide layer before reaching the gate electrode. In these conditions oxide transport can affect \( I_G \). Nevertheless, its effect has not been thoroughly investigated yet.

In most cases, \( I_G \) MC simulation adopts the ballistic approach (BAL): only transport in the silicon channel is taken into account, and \( I_G \) is evaluated by weighting each electron hitting the interface with a local transmission probability \( P_T \), computed assuming carriers to be ballistic [2, 3], i.e. neglecting oxide transport (Fig. 1).

Recently, coupled oxide/silicon transport has been included in the MC model [4, 5, 6]. However, in Ref. [4] silicon and oxide transport were simulated in sequence (non self-consistently) and only in MOS capacitors (1D case). References [5, 6] did not pay particular attention to the effect of the 2D field profile present in MOS transistors, and report opposite results about the effect of oxide scattering in the image force potential well. In [5] it is suggested that oxide scattering in the image force potential well reduces \( I_G \) of orders of magnitude, while it is reported in [6] that \( I_G \) is reduced at most by a factor of two.

In this paper, we report for the first time an in depth investigation of the effect of oxide transport and different injection model on \( I_G \) for realistic 2D field profiles. By comparing measurements and simulations it is shown that oxide transport impacts appreciably hot electron \( I_G \) when the oxide field at the drain end of the channel is repulsive \( F_{ox} < 0 \). In this case, self-consistent coupled silicon/oxide simulation is needed to quantitatively assess \( I_G \). On the contrary, when \( F_{ox} > 0 \), the ballistic model is accurate enough. In addition, it is reported that oxide scattering in the image force potential well does not significantly reduce \( I_G \).

This paper is arranged as follows. Section 2 describes the physical models adopted and investigated, whereas results are reported and discussed in Sec. 3. Section 4 addresses the issue of the scattering in the image force potential well. Finally, Sec. 5 draws some conclusions.

2. Models

The Monte Carlo program (FURBO) features the anisotropic (full) band structure of silicon [7] computed with the nonlocal pseudopotential method [8], and the most important scattering mechanisms, namely phonon, impact ionization (II), ionized impurity and surface scattering, as well as electron-electron and plasmon-electron scattering. We adopted the impact ionization scattering rate from full band calculation of Ref. [9], while phonon
scattering was adjusted to reproduce a large number of experimental data sensitive to both the low and high energy part of the electron distribution such as drift velocity, universal mobility curve, impact ionization coefficient, quantum yield, homogeneous injection probability, gate current when oxide transport is not important (see Sec. 3).

For oxide simulation, a parabolic band with \( m_{ox} = 0.5m_0 \) is assumed for electrons. Polar optical phonon scattering (63- and 153-meV modes) has been implemented as in [12], while inelastic acoustic phonon and II scattering have been treated as in [13]. Scattering parameters have been chosen to reproduce the scattering rates of Ref. [13], therefore the present model provides the same energy distributions and average energy of Ref. [13] that compare favorably with experimental results (Fig. 2).

where \( E_C \) is the oxide conduction band. If \( k_\perp \) is real, the particle is put just inside the oxide (point \( a \) in Fig. 3) with \( P_T \) is evaluated, a new particle is created in the position corresponding to \( k_\perp = 0 \) (point \( b \) in Fig. 3) with statistical weight \( w_{ox} = w_{si}P_T \), and the particle in the silicon is reflected back with \( w_{si} \) reduced by \( w_{ox} \). Moving in the oxide the new particle can reach the gate/oxide interface, in this case it is removed from the simulation and \( I_G \) is updated, or be scattered back in the silicon.

Simulation results shown in the next Section have been obtained assuming a trapezoidal (TRPZ) barrier (as in Fig. 3). Effect of image force barrier lowering will be discusses in Sec. 4.

### 3. Results and Discussion

Figure 4 compares experimental and simulated \( I_G \) for a thick oxide device with \( L_G = 0.8 \mu m \), \( t_{ox} = 15nm \) in comparison with experimental data (line).

\[ \frac{\hbar^2 k_\perp^2}{2m_{ox}} = \epsilon_\perp = E_{TOT} - E_C - \frac{\hbar^2 k_\parallel^2}{2m_{ox}} \tag{1} \]
Figure 5. Flux distributions provided by C-MC model for the same device of Fig. 4. $F_{ox} > 0$ at the left of the arrow, $F_{ox} < 0$ at the right.

and the gate flux (OUT) along the channel as provided by the C-MC model. In the left frame, $F_{ox} > 0$ always and IN and OUT fluxes nearly coincide. Although particles do scatter in the oxide, $F_{ox}$ pushes them toward the gate anyway and only a negligible fraction of them go back. When $V_{GS} < V_{DS}$ (Fig. 5, right), the picture is similar for the portion of the channel where $F_{ox} > 0$, while, when $F_{ox} < 0$, most of the particles go back in the silicon substrate.

Fluxes in Fig. 5 accounts for all particles injected into the oxide, even those that do not have the $\epsilon_TOT$ classically necessary to reach the gate ($\epsilon^*$ in Fig. 1). In order to point out the physical difference between BAL and C-MC approaches, Fig. 6 shows the ratio of the OUT and IN fluxes of only those particles with $\epsilon_TOT > \epsilon^*$ ($R_J = J_{OUT}(\epsilon_TOT > \epsilon^*)/J_{IN}(\epsilon_TOT > \epsilon^*)$), i.e. the ratio between particles that actually reach the gate and those that would have reached it according to the BAL model. Whenever $F_{ox} > 0$, $R_J$ is $\approx 1$, i.e. most particles with $\epsilon_TOT > \epsilon^*$ reach the gate. In contrast, when $F_{ox} < 0$, only a small fraction of the particles with $\epsilon_TOT > \epsilon^*$ reaches the gate, while most of them is back-scattered.

Figure 6. Ratio of the OUT and IN fluxes with $\epsilon_TOT > \epsilon^*$ for the same device of Fig. 4. Arrows mark the position where $F_{ox} = 0$.

Figure 7. Ratio of the OUT and IN fluxes with $\epsilon_{TOT} > \epsilon^*$ for a thin oxide device. Arrows mark the position where $F_{ox} = 0$.

Qualitatively the same results have been obtained on a thinner oxide device (Fig. 7) operating at $qV_{DS} < \epsilon_B$ as long as $I_G$ is dominated by hot carriers emitted over the barrier.

4. Comments

Figure 8 shows the energy profiles considered to study the effect of oxide scattering in the image force potential well. For the BL profile, electrons experience an high scattering rate because of the high energy [5] and, if they fall below the top of the barrier, they are reflected back in the silicon. In contrast, with the SIMPLE profile electrons undergo a reduced scattering rate (because of the smaller energy) and $F_{ox} = 0$ makes it easier to reach the gate electrode anyway [5].

Figure 8. Left: full image force correction (BL). Right: simplified correction (SIMPLE).

Figure 9 compares simulations and measurements of injection probability ($P_{inj}$) for the simple experimental condition of homogeneous substrate hot electron injection [14]. BAL and C-MC model with trapezoidal barrier well agree with experiments. C-MC simulations with the image force corrections of Fig. 8 overestimate $P_{inj}$ for $V_{TOT} = V_{SB} + 2\Phi_F > \epsilon_B/q$ because of the reduced barrier, while they underestimate $P_{inj}$ for low $V_{TOT}$ because tunneling was not included in the simulation to single out
only the effect of oxide scattering. However, BL and SIMPLE profiles provide essentially the same results demonstrating that oxide scattering in the image force potential well does not significantly change $I_G$ [6].

To check this conclusion we repeated the same exercise of Figs. 6, 7 computing the ratio of the OUT and IN fluxes with $\epsilon_{TOT}$ larger than the top of the barrier. This ratio turned out to be at most two [6]. If we assume that the effect of oxide scattering in the region where $F_{ox} < 0$ simply reduces $I_G$ by $\exp(-d/\lambda_e)$, where $d$ is the path length in the oxide conduction band and $\lambda_e$ is some effective energy relaxation length, this result and the ones in Figs. 6, 7 are consistent with $\lambda_e \approx 1 - 2nm$, in agreement with experimental and theoretical results of photoemission [6]. Moreover, this value of $\lambda_e$ is also consistent with the energy relaxation time $\tau_e \approx 20fs$ given by C-MC simulations if $\lambda_e$ is estimated as $\lambda_e = v_d \tau_e$, where $v_d \approx 10^7cm/s$ is the oxide drift velocity.

5. Conclusions

In this paper we have investigated the impact of oxide transport on the gate current of MOS transistors by means of coupled self-consistent silicon/oxide Monte Carlo simulation, also comparing different injection models.

It has been shown that oxide transport is not important when $F_{ox} > 0$. In this case, the widely used ballistic assumption is accurate enough. On the contrary, when a portion of the channel experiences a negative field, oxide transport plays an important role that must be taken into account for accurate evaluation of the hot carrier induced gate current. This observation holds true even for thin oxide devices as long as $I_G$ is made of hot electrons emitted in the oxide conduction band.

In addition, it has also been shown that oxide scattering in the image force potential well does not significantly change $I_G$. 

Figure 9. Homogeneous injection probability provided by different injection models (symbols) in comparison with experimental data (line) from [14].