Impact of Non-Stationary Transport Effects on Realistic 50nm MOS Technology

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ABSTRACT

This paper highlights the impact of non-stationary transport on performances of deep submicron CMOS bulk technology. We present a quantitative analysis of technology influence on the needed level for carrier transport modeling (Drift-Diffusion versus Energy Balance). The analysis is performed on realistic devices, showing which electrical features have to be taken into account for evaluating the performances of advanced device architectures (down to 50nm gate length). An original point of this work is the investigation of technology influence (channel doping and LDD doping) on injection velocity at source side and on drain current. We conclude that specific engineering of access region have to be envisaged for taking full advantage of non-stationary effects on nowadays device performances.

Keywords: Non-stationary effects, velocity overshoot, impact ionization, MOS technology, numerical simulation.

1 INTRODUCTION

When gate length of CMOS devices are scaled down in the sub-0.1μm domain, phenomena like non-stationary effects are no longer negligible for the device operation, but they become preponderant and have to be taken into account in the device simulation. For these ultimate devices, it is now well established that the classical Drift-Diffusion (DD) is no longer satisfactory because this model fails to predict non-stationary effects, such as velocity overshoot and carrier diffusion due to electronic temperature gradients. Moreover, DD model neglects the dependence of impact ionization on carrier energy. Hence advanced models become mandatory for accurate simulation of nowadays devices, even if the question of the needed accuracy of modeling level for practical applications still remains.

Different models exist, all based on the solution of the semi-classical Boltzmann Transport Equation (BTE). The most precise is Monte-Carlo (MC) simulation [1] which provides very accurate physical insights of device operation. However, the huge calculation time makes this approach difficult to use for technology optimization. Consequently, we preferred to use an intermediate modeling level, the Energy Balance (EB) model, which is available in commercial tools [2]. This model combines the advantage of satisfactory accuracy and fast calculations, and is very suitable for device engineering.

In this paper we analyze quantitatively the real impact of technology (gate length, channel and/or LDD doping) on the needed level for carrier transport modeling (DD versus EB) and the results are applied to realistic devices obtained from process simulation.

2 SIMULATED DEVICES

Simplified devices (constant channel doping, no LDD, no pockets) are generally used in simulation for the analysis of non-stationary effects. However doping profiles strongly influence spatial variations of electric field, consequently they will have a significant impact on non-stationary effects. For this reason realistic devices are needed for accurate conclusions on non-stationary effects. In this work we use devices obtained by simulating the technological process of our 50nm technology [3]. Devices are designed with t_{ox}=2.3nm, extensions and pockets and non-constant channel doping. They are optimized for low leakage current, I_{off}<0.1nA/μm (for the shorter device), because DIBL is a major concern for an accurate analysis of velocity overshoot [4]. Longer devices have the same structure, which ensures low DIBL.

3 SIMULATION MODELS

Simulations were performed with DD and EB models of Atlas [2]. Compared to DD, EB model takes into account two additional equations: the conservation of carrier energy (eq.1) and the energy flux (eq. 2).

$$\mathrm{div}S_n = -J_n \nabla\varphi - \frac{3}{2} k\, n \frac{T_n - T_L}{\tau_{rel}} - W_n \qquad (1)$$

$$S_n = -K_n \nabla T_n - \frac{k\Delta_n}{q} J_n T_n \qquad (2)$$

where S_n=energy flux, ϕ=potential, Jn=electron current density, μ_n=electron mobility, W_n=energy density loss rate, τ_{rel}=energy relaxation time, T_L=lattice temperature,

T_n=electron temperature, Δ_n = model coefficient. K_n and W_n are given by [2]:

$$K_n = qn\mu_n\left(\frac{k}{q}\right)^2 \Delta_n T_n \tag{3}$$

$$W_n = \frac{3}{2}n\frac{k(T_n - T_L)}{\tau_{rel}}\lambda_n + \frac{3}{2}kT_n\lambda_n R_{SRH} + E_g(G_n - R_n{}^A) \tag{4}$$

with R_{SRH} = SRH recombination rate, G_n= impact ionization rate, $R_n{}^A$ = Auger recombination rate.

Moreover, in EB model, physical parameters are no longer electric field-dependent, but they become energy-dependent. In the following we consider the same models in DD and EB for the main parameters: mobility, carrier statistics and recombination.

The energy relaxation time τ_{rel}, (eq. 1 and 4) is a critical parameter in EB model. τ_{rel} governs the magnitude of non-stationary effects, consequently it has a strong impact on the drain current (as shown in figure 1).

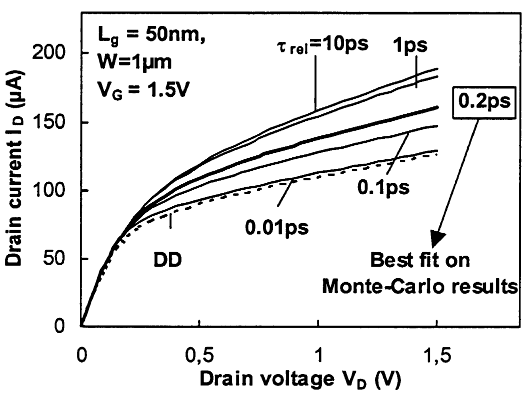

Figure 1: Influence of the energy relaxation time on output $I_D(V_D)$ characteristics.

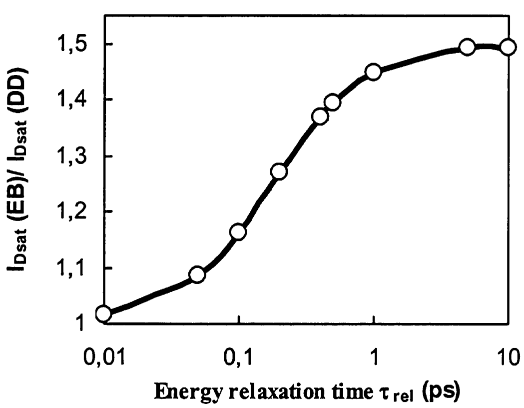

Figure 2: Variation of ratio $I_{Dsat}(EB)/I_{Dsat}(DD)$ with τ_{rel}.

The variation of I_{Dsat} (I_{Dsat} is the drain current at V_G=V_D=1.5V) with the energy relaxation time is linear for τ_{rel} between 0.05ps and 0.5ps, and becomes saturated without this range (figure 2). When τ_{rel} decreases under 0.01ps, the EB current reaches, as expected, the DD value.

Very controversial values for the energy relaxation time (from 0.1 to 1ps) are given in the literature, hence we calibrated our simulator on MC data. The best fit between EB and MC results was obtained for τ_{rel}=0.2ps, consequently this value has been used in our simulations.

4 NON-STATIONARY EFFECTS: VELOCITY OVERSHOOT

Velocity overshoot is the immediate consequence of the finite time needed before the carrier energy reaches equilibrium with the electric field. In the classical DD model, this time is assumed to be zero, therefore DD completely neglects non-stationary effects and velocity overshoot. These phenomena explain the difference between drain currents predicted by DD and EB models:

(a) at high drain voltage, the drain current is strongly underestimated in DD compared to EB, because of the velocity overshoot (figure 3a).

(b) at low drain voltage, DD and EB models give the same current, as expected, even in very short channels. The reason is that non-stationary effects are negligible at low V_D, which leads to almost similar velocity profiles in the channel for both models (figure 3b).

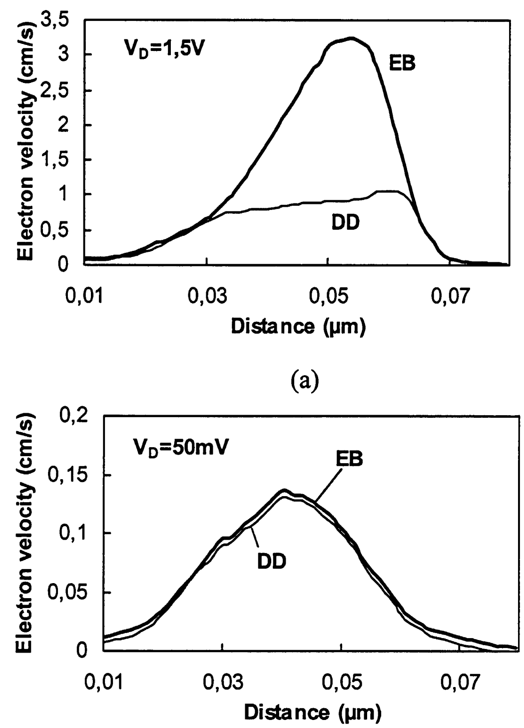

Figure 3: Profiles of velocity at 10Å channel depth obtained by EB and DD at (a) high and (b) low V_D (L_g=50nm, V_G=1.5V).

The difference between drain current predicted by DD and by EB depends significantly on the gate length, channel doping and LDD doping. In the following we discuss the influence of each parameter on the impact of non-stationary effects on device performances.

4.1 Influence of the channel length

When the gate length increases, the difference between DD and EB decreases (figure 4), and becomes negligible for L_g>0.25μm. The $I_{Dsat}(EB)/I_{Dsat}(DD)$ ratio is 1.3 for L_g=50nm and 1.02 for L_g=0.25μm (figure 5). The practical consequence of this analysis is that an inferior gate length limit for using the classical DD model can be evidenced and in our case this limit is about 0.25μm.

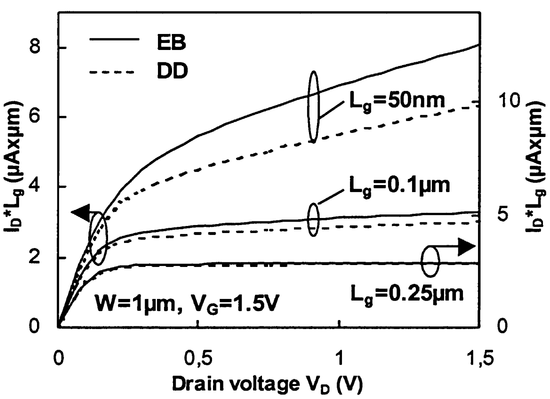

Figure 4: I_D*L_g (V_D) characteristics simulated with EB and DD for different L_g.

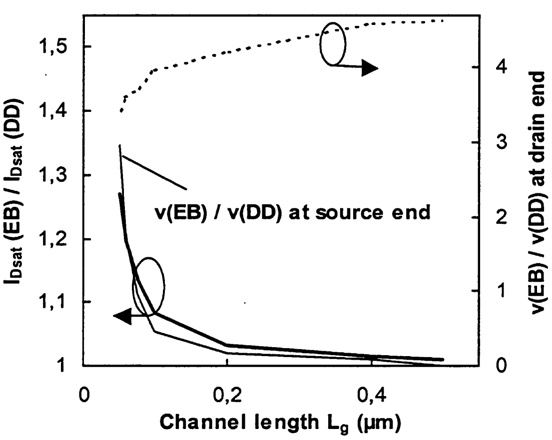

Figure 5: Variation of ratio $I_{Dsat}(EB)/I_{Dsat}(DD)$ and v(EB)/v(DD) at source and drain-end with L_g.

Figure 6 presents the variation of EB velocity along the channel for different gate lengths. An interesting result is that drain-side velocity increases slowly with the channel length, while the opposite behavior was expected. The explanation is that carriers are strongly accelerated in short channels, but they cannot reach the maximum velocity, being rapidly collected in the drain.

Velocity profiles in the channel (figure 6) show that velocity overshoot is extremely important at drain side, but this phenomenon is not reflected in I_D, because the carrier concentration decreases near the drain. Moreover, the drain current is controlled by the injection at source-end [5], therefore I_D enhancement when L_g decreases is due to velocity increase at source. Indeed, figure 7 shows that source velocity increases for shorter channels, which is reflected in higher I_D.

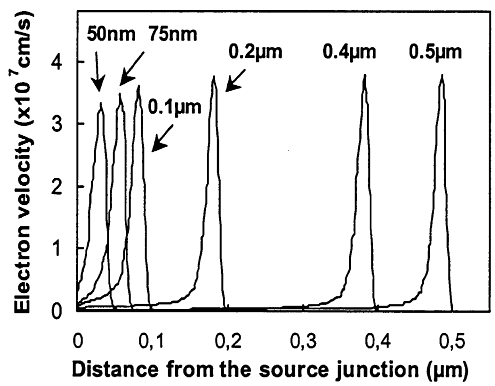

Figure 6: Profile of velocity in the channel at 10Å depth for various L_g (V_G=V_D=1.5V).

The argument of source-side controlled drain current is also confirmed by the I_D enhancement in EB versus DD. For L_g=50nm the ratio $I_{Dsat}(EB)/I_{Dsat}(DD)$=1.3, while at drain the velocities ratio v(EB)/v(DD)=3.5 (at V_G=V_D=1.5V). On the other hand, v(EB)/v(DD) at source is 1.33, in perfect agreement with the currents ratio. The same good match between $I_{Dsat}(EB)/I_{Dsat}(DD)$ and v(EB)/v(DD) at source is obtained for all channels, as shown in figure 5.

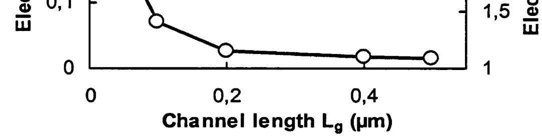

Figure 7: Drain and source–end velocity as a function of the channel length, calculated by EB model.

4.2 Influence of channel/LDD doping

Lower channel doping or higher LDD doping, lead to higher electric field variations at the source side, implying higher velocity. The evaluation of the impact of doping-induced velocity enhancement on the drain current is quite difficult because the doping changes modify the threshold voltage (i.e. the drain current). Our idea was to consider the ratio $I_D(EB)/I_D(DD)$ for eliminating at first order the influence of doping changes on threshold voltage. Results in Table 1, obtained for various channel and LDD doses, show that higher source velocity is reflected in more important enhancement of the drain current in EB compared with DD. This conclusion opens the perspective for specific engineering of the access regions (LDD, pockets, channel doping) to improve injection velocity, *separately* from V_T adjustments.

Implanted Channel Dose (cm^{-2})	Implanted LDD Dose (cm^{-2})	v_{source} ($\times 10^7$cm/s)	$I_{Dsat(EB)}/I_{Dsat(DD)}$
$1x10^{13}$	$0.8x10^{14}$	0.97	1.34
$2x10^{13}$		0.73	1.31
$3x10^{13}$		0.58	1.28
$3x10^{13}$	$0.5 x10^{14}$	0.54	1.22
	$1x10^{14}$	0.78	1.33
	$2x10^{14}$	1.14	1.45

Table 1: Impact of channel / LDD doping (L_g=50nm).

This analysis has emphasized important conclusions for two essential aspects of device engineering:

(a) *device modeling:* we have evidenced the needed modeling level as a function of the device geometry.

(b) *device designing:* we have presented a quantitative evaluation of the technological parameters allowing to maximize the impact of velocity overshoot on the device performances.

Finally, it must be noted that quantization of carrier energy at source side should modify the injection conditions and therefore the drain current. The real impact of quantum effects on the electronic transport at source remains a key point, which needs thorough investigation.

5 IMPACT IONIZATION

Impact ionization is an energy-threshold phenomenon, hence an electric field-dependent model (as DD) leads to erroneous prediction of impact ionization-related effects. DD model strongly overestimates the impact ionization (i.e. the breakdown initiation) not only in short channels, but also in long channels, as shown in figure 8. Therefore, accurate simulation of impact ionization needs an energy-dependent model even at higher lengths, while from the viewpoint of non-stationary effects DD model is satisfactory for L_g>0.25µm.

Accurate simulation of impact ionization is a very important issue for simulating substrate current and hot carrier effects in bulk devices. This is also a critical point for reproducing accurate $I_D(V_D)$ curves and kink region in partially depleted SOI devices [6].

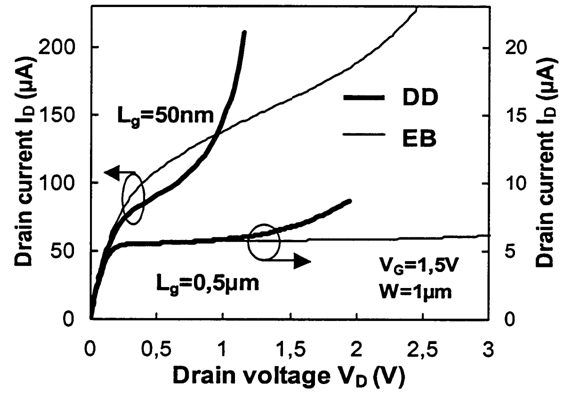

Figure 8: $I_D(V_D)$ curves obtained by EB and DD with impact ionization at different gate lengths.

6 CONCLUSION

This paper presents the impact of the modeling level on the performances of CMOS devices in 50nm bulk technology. Accurate conclusions on non-stationary transport demand the use of realistic devices in simulation. We have shown that for taking into account the impact of non-stationary effects on drain current, advanced simulation models are necessary for channel lengths below 0.25µm, while for impact ionization an energy dependent model must be considered even for much longer channels. The current enhancement due to non-stationary transport must always be referred to the velocity at the source side, and not to drain. Finally, thorough investigation of channel/LDD doping influence on injection velocity opens the perspective for specific engineering of the access regions (LDD, pockets, channel doping) to take full advantage of non-stationary effects on performances of nowadays devices.

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