Non-Stationary Transport Effects: Impact on Performances of Realistic 50nm MOSFET Technology

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Abstract

We analyze quantitatively the real impact of technology on the needed level for carrier transport modeling. The results, based on theoretical analyses, are applied to existing devices. This work shows which recipes must be used to evaluate 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. The results open the perspective of specific engineering of access regions in order to take full advantage of non-stationary effects on the drain current.

1. Introduction

For MOSFETs with gate length ranging around and below 0.1µm, it is now well established that the Drift-Diffusion (DD) model fails to predict velocity overshoot and carrier diffusion due to electronic temperature gradients. Moreover, this model neglects the dependence of hot-carrier effects on carrier energy, giving unphysical results for issues related to impact ionization and reliability. 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. Solutions like Monte-Carlo (MC) simulation are very accurate [1], but CPU-consuming, therefore difficult to be applied for technology optimization. For this reason we preferred to use an advanced energy transport model available in commercial tools [2], which combines the advantages of satisfactory accuracy and fast calculations.

After a short description of the simulated devices, we calibrate the transport model on MC data. Then we analyze how non-stationary effects impact the device behavior and the dependence of this impact on main technological parameters.

2. Simulated Devices

Many previous works are performed on simplified devices (constant channel doping, no LDD, no pockets). Since doping profiles strongly influence the spatial variations of electric field, realistic devices are needed for accurate conclusions on non-stationary effects.

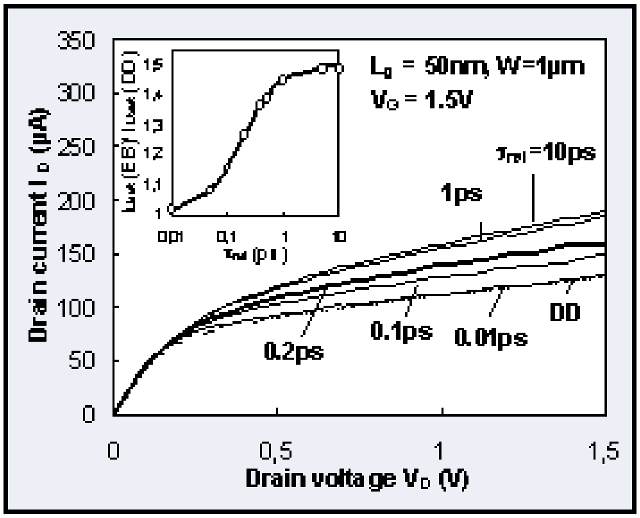

Figure 1. Influence of energy relaxation time, τ_{rel}, on $I_D(V_D)$ curves (inset: variation of ratio $I_{Dsat}(EB)/I_{Dsat}(DD)$ with τ_{rel}).

Consequently we have decided to use devices obtained by simulating the technological process of our 50nm technology [3]. Devices are designed with LDD extensions and pockets, and the oxide thickness is 2.3nm. It was demonstrated that DIBL is a major concern for an accurate analysis of velocity overshoot [4], consequently we optimized the shorter device (L_g=50nm) to have an I_{off} lower than 0.1nA/µm. Longer devices have the same structure, which ensures low DIBL.

3. Calibration of Energy Balance Model

The simulations were performed with Drift-Diffusion (DD) and a modified Energy Balance (EB) models of ***ATLAS*** (Silvaco). The main parameters (mobility, carrier statistics, recombination) are expressed by the same models in EB and DD, with the difference that in EB they are no longer electric field dependent, but carrier energy dependent [2]. Compared to DD, EB considers two additional equations: the conservation of the carrier energy and the energy flux. A critical parameter in EB model is the energy relaxation time, τ_{rel}, which governs the magnitude of the non-stationary effects. Figure 1 shows that τ_{rel} has a strong impact on terminal currents. The variation of I_{Dsat} (drain current at V_G=V_D=1.5V) versus τrel is linear for τ_{rel} between 0.05ps and 0.5ps, and becomes saturated outside this range (inset in Figure 1).

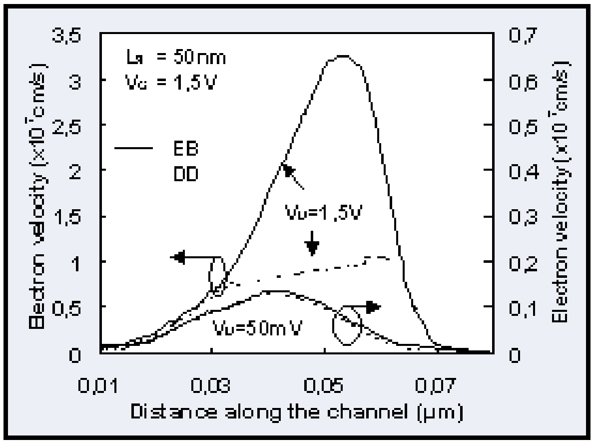

Figure 2. Profiles of velocity at 10Å channel depth obtained by EB and DD at low and high drain voltage.

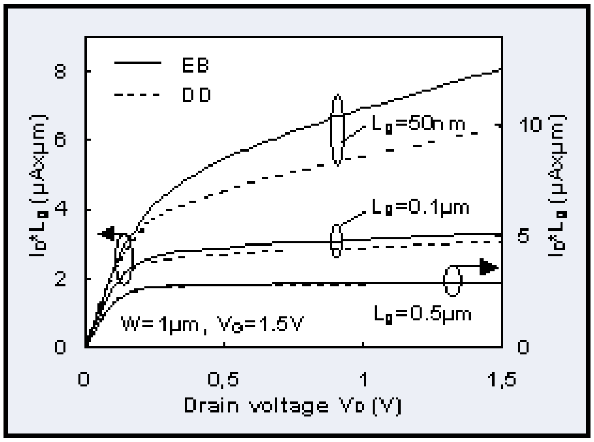

Figure 3. I_D*Lg (V_D) characteristics simulated with EB and DD for different channel lengths.

When τ_{rel} decreases, carrier energy reaches equilibrium with electric field faster, which implies less non-stationary effects. Moreover, for τ_{rel} <0.01ps the DD regime is attained and the EB current is limited to the value predicted by DD model. Since very controversial values of τ_{rel} (from 0.1 to 1ps) are given in the literature, we calibrated our simulator on MC data, the best match between EB and MC results being obtained for τ_{rel} = 0.2ps.

Impact ionization is modeled by the Selberherr [2] model in both DD and EB. In EB the effective field depends on the carrier energy, through an energy relaxation length related to τ_{rel} [2].

4. Simulation Results

4.1. Velocity Overshoot

The first effect of non-stationary transport in very short channels is the velocity overshoot, which impacts directly the drain current. The electric field-dependence in DD model does not allow to simulate the velocity overshoot phenomenon. This explains the difference between the drain current obtained by EB and DD: (a) at high V_D the EB drain current is significantly higher, because in DD model the velocity is limited to the saturation value (about 10^7 cm/s, Figure 2), leading to under-estimated drain current; (b) at low V_D however, the velocity profiles in the channel are almost the same for both models (Figure 2), even in very short channels, which implies the same drain current level.

It is worth noting that the difference between currents predicted by EB and DD depends strongly on the channel length, channel doping and LDD region doping. We discuss in the following the impact of each parameter.

Channel length. When the channel length increases, the difference between DD and EB decreases as shown in Figure 3, and becomes negligible for L_g>0.25µm. I_{Dsat}(EB)/I_{Dsat}(DD) ratio is about 1.3 for L_g=50nm and 1.02 for L_g=0.25µm. The practical consequence of this analysis is that we can evidence an inferior limit of the channel length for using the classical DD model. In our case this limit is about 0.25µm, therefore for shorter gate lengths the use of advanced models is necessary for obtaining accurate simulation results. We mention that this limit can also slightly vary as a function of gate-channel and source/drain-channel architecture.

Figure 4 presents the variation of the EB electron velocity along the channel for different L_g. An interesting result is that the velocity overshoot at the drain side increases slowly with L_g, while the opposite behavior was expected. The explanation is that carriers are strongly accelerated in short channels, but they cannot reach the maximum velocity, as they are rapidly collected in the drain. When Lg increases the maximum velocity increases and becomes saturated for L_g=0.2µm. However, this phenomenon is

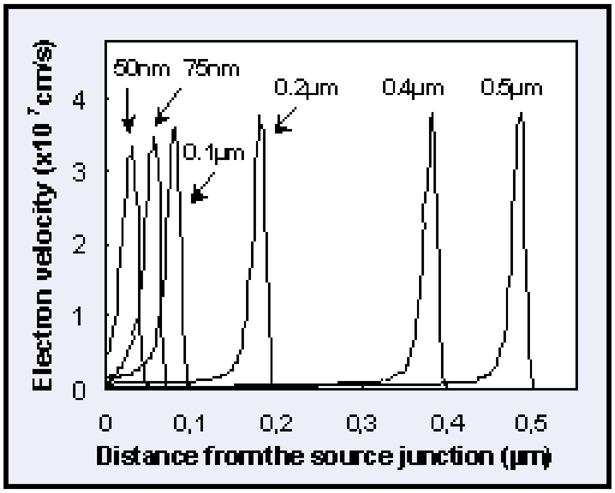

Figure 4. Profiles of velocity in the channel at 10Å depth for various L_g (V_G=V_D=1.5V).

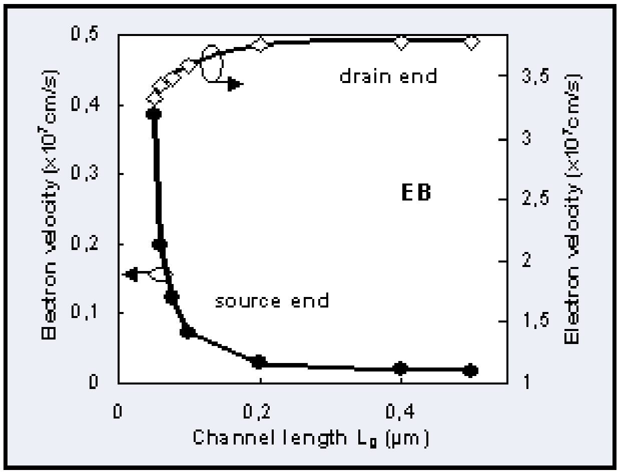

Figure 5. Drain and source–end velocity obtained by EB model as a function of the channel length (V_D=V_G=1.5V).

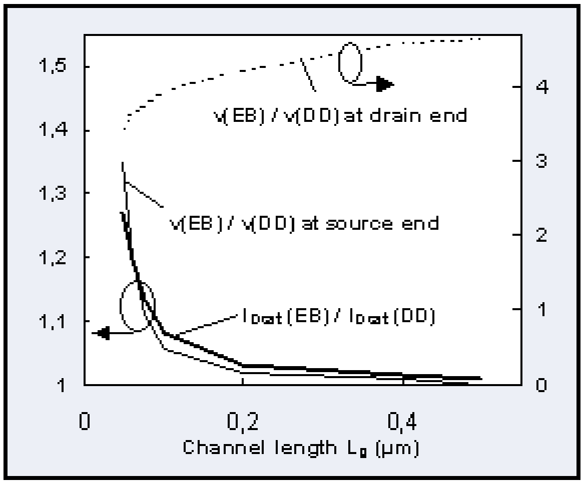

Figure 6. Variation of ratio I_{Dsat}(EB)/I_{Dsat}(DD) and v(EB)/v(DD) at source and drain end as a function of the gate length (V_D=V_G=1.5V).

not reflected in the drain current because near the drain the increase of the velocity with L_g is accompanied by a strong decrease of the carrier concentration.

Moreover, it has been shown that the current enhancement is due to the increase in the velocity at the source side, where the carrier concentration is gate controlled [5]. Indeed, Figure 5 shows that the source velocity increases for shorter channels (because of a higher electric field at the source end), which is reflected by a higher current. The argument of source-side controlled current is also confirmed by the current enhancement in EB compared with DD (Figure 6). At the drain side the ratio between velocity (v) in EB and DD is about 3.5 for L_g=50nm, while the current increases only by 30%. This last value is in good agreement with the ratio between velocities in EB and DD at the source side. The same conclusions are obtained for longer channels (Figure 6).

Channel/LDD doping. For lower channel doping or higher LDD doping, the electric field at the source side increases, which implies a higher velocity (Table 1). However, changes in doping imply V_T variations, which makes difficult the evaluation of the impact of doping induced-velocity enhancement on I_D. A first order decorrelation of the two effects can be obtained by taking into account the ratio I_{Dsat}(EB)/I_{Dsat}(DD). Higher velocity is reflected by a more important increase in the drain current, independent on doping (Table 1). This result opens the perspective of specific engineering of the access regions (LDD, pockets, channel doping) to improve injection velocity, *separately* of V_T adjustments. This type of evaluation only begins to appear in the literature [6].

We have also verified the importance of using realistic devices: simulations on simplified structures overestimate the impact of non-stationary effects on the terminal currents.

Finally, it is important to note that quantum effects will have to be taken into account for a more accurate analysis of the impact of velocity overshoot on drain current.

Implanted Dose ($\times 10^{14}$cm^{-2})		vsource (_10^7cm/s)	$I_{Dsat(EB)}$/$I_{Dsat(DD)}$
Channel (LDD dose: 0.8 $\times 10^{14}$)	0.1	0.97	1.34
	0.2	0.73	1.31
	0.3	0.58	1.28
LDD (Channel dose: 3 $\times 10^{13}$)	0.5	0.54	1.22
	1	0.78	1.33
	2	1.14	1.45

Table 1. Impact of channel/LDD doping (L=50nm) on source velocity and drain current.

4.2. Impact Ionization

While the classical DD model can be satisfactory for simulating channels longer than 0.25µm, impact ionization needs an energy dependent-model even at much higher lengths. The DD model depends on electric field, which leads to a strong over-estimation of impact ionization for all channel lengths.

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Figure 7 presents $I_D(V_D)$ curves for short and long channels, illustrating the over-estimation of the avalanche region by the DD model. Therefore EB model must be used for impact ionization at all channel lengths. 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 [7].

5. Conclusion

In this paper we have presented the impact of the modeling level on the electrical behavior of 50nm bulk MOSFET technology. For accurate conclusions, realistic devices have been considered in simulation. The current enhancement due to non-stationary effects must always be referred to the velocity at the source side of the device, and not to drain side. For reproducing the impact of velocity overshoot advanced models are necessary for channel lengths below 0.25µm, while for impact ionization an energy dependent model must be considered even for much higher dimensions. An original analysis in this work is the quantitative evaluation of technological parameters impact on injection velocity and drain current. The results show that for taking full advantage of non-stationary effects on device performances specific engineering of access regions have to be envisaged.

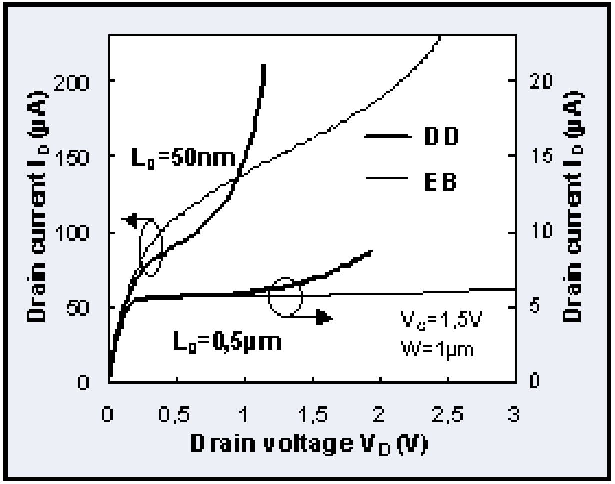

Figure 7. $I_D(V_D)$ curves obtained by EB and DD with impact ionization model at different L_g.

6. References

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