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

D. Munteanu, G. Le Carval, G. Guegan
LETI, CEA / Grenoble, Microelectronics Department
17 rue des Martyrs, 38054 Grenoble, France
e-mail: munteanu@dmel.ceng.cea.fr

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.

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 (Lg=50nm) to have an Ioff 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, τrel, which governs the magnitude of the non-stationary effects. Figure 1 shows that τrel has a strong impact on terminal currents. The variation of I_Dsat (drain current at V_C=V_D=1.5V) versus τrel is linear for τrel between 0.05ps and 0.5ps, and becomes saturated outside this range (inset in Figure 1).
When \( \tau_{\text{rel}} \) decreases, carrier energy reaches equilibrium with electric field faster, which implies less non-stationary effects. Moreover, for \( \tau_{\text{rel}} < 0.01 \text{ps} \) the DD regime is attained and the EB current is limited to the value predicted by DD model. Since very controversial values of \( \tau_{\text{rel}} \) (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 \( \tau_{\text{rel}} = 0.2 \text{ps}. \)

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 \( \tau_{\text{rel}} \) [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 \( L_g > 0.25 \mu m \).

\[ \frac{I_{\text{Idsat(EB)}}}{I_{\text{Idsat(DD)}}} \] ratio is about 1.3 for \( L_g = 50 \text{nm} \) and 1.02 for \( L_g = 0.25 \mu m \). 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 0.25 \( \mu m \), 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 \( L_g \) increases the maximum velocity increases and becomes saturated for \( L_g = 0.2 \mu m \). However, this phenomenon is
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 \( L_g=50\,\text{nm} \), 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 \( I_{\text{sat(EB)}}/I_{\text{sat(DD)}} \). 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.

### Table 1. Impact of channel/LDD doping (\( L=50\,\text{nm} \)) on source velocity and drain current.

<table>
<thead>
<tr>
<th>Implanted Dose (x10^14cm^-2)</th>
<th>( v )source (x10^10cm/s)</th>
<th>( I_{\text{sat(EB)}}/I_{\text{sat(DD)}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel (LDD dose: 0.8 x10^14)</td>
<td>0.1 0.97</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>0.2 0.73</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>0.3 0.58</td>
<td>1.28</td>
</tr>
<tr>
<td>LDD (Channel dose: 3 x10^13)</td>
<td>0.5 0.54</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>1 0.78</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>2 1.14</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Continued on page 12...
the date or time on the machine may have been modified. If the system clock is more than one hour out of sync with local time, correct the machine time, delete the folder \Temp\sflm and reboot the PC

the dongle may have been damaged. To check this run the following command from the DOS prompt

c:\Silvaco\bin\showid.exe -time

the output from this should be self explanatory. This will also display the machine name and HASP number. The machine name should be repeated in the file c:\Silvaco\var\sflmserver and the HASP number should be the same as the line in the license file that starts with LM_HOSTIDS.

If these are not sufficient to correct the problem contact support@silvaco.com.

Q. Is there any documentation available to help in troubleshooting installation problems?

A. After the software is installed, the user can find an extensive list of troubleshooting tips in the file entitled FAQ which resides in the Shortcuts folder as well as in c:\Silvaco\var\FAQ.txt

Call for Questions
If you have hints, tips, solutions or questions to contribute, please contact our Applications and Support Department
Phone: (408) 567-1000 Fax: (408) 496-6080
e-mail: support@silvaco.com

Hints, Tips and Solutions Archive
Check out our Web Page to see more details of this example plus an archive of previous Hints, Tips, and Solutions
www.silvaco.com

...continued from page 6

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.

6. References