Ultra-small MOSFETs: The Importance of the Full Coulomb Interaction on Device Characteristics

W. J. GROSS^a, D. VASILESKA^{b,*} and D. K. FERRY^b

^aIntel Corp., Chandler, AZ 85226; ^bDepartment of Electrical Engineering and Center for Solid State Electronics Research Arizona State University, Tempe, AZ 85287-5706

We discuss a full three-dimensional model of an ultra-small MOSFET, in which the transport is treated by a coupled EMC and molecular dynamics (MD) procedure to treat the Coulomb interaction in real space. The inclusion of the proper Coulomb interaction affects both the energy and momentum relaxation processes, but also has a dramatic effect on the characteristic curves of the device. We find that the short-range $e-e$ and $e-i$ terms, combined with discrete impurity effects, is also needed for accurate measurement of the device threshold voltage.

Keywords: Direct Coulomb interaction; Device modeling; Discrete impurities

1. INTRODUCTION

As the density of integrated circuits continues to increase, there is a need to shrink the dimensions of the devices of which they are comprised. Currently, $0.18\text{ }\mu\text{m}$ is the state-of-the-art process technology, but even smaller dimensions are expected in the near future, and by the end of 2009, the leading edge devices will employ $0.05\text{ }\mu\text{m}$ gate lengths and have oxide thickness of 1.5 nm , or less. In simulations of these ultra-small semiconductor devices, a number of important considerations have been approximated in a manner which is not representative of the actual physical interactions within the devices. One of these is the

Coulomb interaction [1]. This Coulomb interaction has two parts: first, the nature of discrete impurities and how this affects device performance, and, secondly, how the Coulomb interaction affects the *transport* of the carriers through the device. These effects become even more important when it is realized that simulations must be carried out in the three-dimensional regime. While simple two-dimensional simulations could suffice today, they will not be adequate for the 50 nm devices of the future, and it is important to have full three-dimensional simulations if the effects discussed here are to be adequately examined.

Most ensemble Monte Carlo (EMC) simulations of small semiconductor devices include the details

*Corresponding author.

for the Coulomb interactions only through a momentum conserving k -space scattering process. In general, this process does not account for significant energy loss (or gain) by an individual carrier [2]. In such simulations, it has been shown the carrier will go several tens of nm that the drain before relaxing their energy and directed momentum. The problem is that the carriers in the channel interact through the Coulomb interaction, not only with impurities and other carriers in the channel, but also with impurities and carriers in the drain and gate [3]. The energy loss mechanism of energetic carriers moving from the channel to the drain is by the emission of plasmons (coupled modes of the drain electrons) [4]. The real Coulomb interaction is long range, though. Hence, it is important to treat the full Coulomb interaction properly in real space.

Previously, we have discussed a full three-dimensional model of an ultra-small MOSFET, in which transport is treated by a coupled EMC and a molecular dynamics (MD) procedure for the Coulomb interaction in real space [5]. The inclusion of the proper Coulomb interaction significantly affects both the energy and momentum relaxation process, but also has a dramatic effect on the characteristic curves of the device. It is important to note that, within our scheme, we have taken special care to avoid double counting of the Coulomb interaction, as the long-range portion is automatically incorporated into the 3D Poisson solution for the self-consistent potential [1]. Only the short-range interaction (which is lost by the discretization used for the device simulation) is treated by the molecular dynamics [5]. Also, the energy loss that would arise from plasmon emission is fully incorporated with no approximations to the screening.

2. COULOMB SCATTERING

There are several consequences of the proper inclusion of the Coulomb interaction. First,

relaxation of the hot carriers in channel occurs in the drain over a few nanometers. In fact, the velocity is already decreasing once the carriers *sense* the presence of the high density of electrons and ionized in the drain. In Figure 1, we plot the velocity in the channel. It can be seen that the velocity peak disappears once the short-range scattering is included, and the velocity actually begins to decay just before the drain. Secondly, the Coulomb “scattering” causes a significant shift in threshold voltage, which directly results in a reduction in actual drain current. The gate-source characteristics are shown in Figure 2, and it is obvious that inclusion of the short-range Coulomb scattering leads to a large threshold shift of 80–100 mV. There has not been a previous discussion of a mobility induced threshold shift in MOSFETs. However, within the “transmission” model of MOSFETs, developed by Lundstrom [6], the drain current is directly given by

$$I_D = TI^{(+)}, \quad (1)$$

where $I^{(+)}$ is the forward current from the source and T is the transmission through the source-channel potential barrier. Lundstrom has

FIGURE 1 Average velocity of the electrons along the channel. The dots marked “mesh only” result from including only the self-consistent potential solution, without the short-range direct Coulomb interaction. This is for $L_g = 80$ nm, centered in the range displayed.

FIGURE 2 Transfer characteristics of a 50 nm device. Solid lines with filled (open) circles correspond to the case when short-range $e-e$ and $e-i$ interactions have been included (omitted) in the simulations.

suggested that this latter is given by

$$T = \frac{\lambda_{\text{mfp}}}{k_B T_L / eE + \lambda_{\text{mfp}}}. \quad (2)$$

It is clear that a change in the mean-free path can be induced by the short-range Coulomb scattering, and this, in turn, can lead to a reduction in the transmission coefficient over the barrier. The result is the need for a larger gate-source field E , and a resulting increase in the threshold voltage.

3. DEVICE CHARACTERISTICS

As a result of the threshold shift, the short-range $e-e$ and $e-i$ interactions have significant influence on the devices output characteristics. Figure 3 shows the output (I_D - V_D) characteristics of devices with $L_G = 50$ nm. The device width is $W_G = 35$ nm, the oxide thickness is $T_{\text{ox}} = 2$ nm, and nominal doping is $N_A = 5 \times 10^{18} \text{ cm}^{-3}$ in the p -region and $N_D = 10^{19} \text{ cm}^{-3}$ in the source and drain. The current is measured by summing the total velocity of the electron beneath the gate and dividing it by the channel length. The total simulation time was 2 ps

FIGURE 3 Output characteristics that clearly show the role of the $e-e$ and $e-i$ interactions on the terminal device characteristics for a device with $L_G = 35$ nm. The device width is $W_G = 35$ nm, and the nominal doping of the substrate is $5 \times 10^{18} \text{ cm}^{-3}$. The oxide thickness is $T_{\text{ox}} = 2$ nm. The gate voltage is varied from 1 to 1.6 V, in increments of 0.2 V.

per bias point, with a measurement taken every fs and averaged over the last 1.6 ps of simulation. The average number of electrons in the channel is less than 100. The device simulations were performed both with, and without, the short-range Coulomb forces added.

When the Coulomb force is included, the current is significantly decreased due to the electron-electron and electron-ion scattering and the consequent threshold shift. This is also a result of a lower mobility of the channel electrons and increased output resistance. Nevertheless, the transconductance is exceedingly high, and the results indicated in Figure 3 suggest a value as high as 1280 mS/mm.

4. CONCLUSIONS

We find that using a corrected Coulomb force in the MD loop in conjunction with a 3D EMC device simulation clearly shows that the short-range $e-e$ and $e-i$ terms play a significant role in the device characteristics. All aspects of the device are modified by proper inclusion of the full

Coulomb interaction. In particular, this is noticeable in the thermalization of the carrier energy at the drain end of the device. This, in turn, leads to reduction of the velocity overshoot effect and, therefore, current drive capabilities of ultrasmall MOSFETs. The inclusion of the short-range $e-e$ and $e-i$ terms, combined with discrete impurity effects, is also needed for accurate measurement of the device threshold voltage.

Acknowledgements

This work was supported by the National Science Foundation and the Office of Naval Research. The authors express their thanks to S. M. Goodnick and M. Fischetti for helpful discussions.

References

- [1] Gross, W. J., Vasileska, D. and Ferry, D. K. (1999). "A Novel Approach for Introducing the Electron-Electron and Electron-Impurity in Particle-Based Simulations", *IEEE Electron Dev. Lett.*, **20**, 463–5.
- [2] Ferry, D. K., Goodnick, S. M. and Hess, K. (1999). "Energy exchange in single-particle electron-electron scattering", *Physica B*, **272**, 538–541.
- [3] Fischetti, M. V. and Laux, S. E. (2000). "Long-Range Coulomb Interactions in Small Silicon Devices: Transconductance and Mobility Degradation", *Proc. MSM 2000*, pp. 461–4.
- [4] See, *e.g.*, Lugli, P. and Ferry, D. K. (1985). "Electron-electron interaction and high field transport in Si", *Appl. Phys. Lett.*, **46**, 596–6.
- [5] Gross, W. J., Vasileska, D. and Ferry, D. K. (2000). "Ultra-Small MOSFETs: The Importance of the Full Coulomb Interaction on Device Characteristics", *IEEE Trans. Electron Dev.*, *in press*.
- [6] Seem, *e.g.*, the review Datta, S., Assad, F. and Lundstrom, M. S. (1998). "The silicon MOSFET from a transmission viewpoint", *Superlatt. Microstruc.*, **23**, 771–80.