Local Iterative Monte Carlo investigation of the influence of electron-electron scattering on short channel Si-MOSFETs

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Abstract

The Local Iterative Monte Carlo (LIMO) technique is used to investigate the effect of electron-electron scattering on hot electron effects in Si-MOSFETS with channel length as short as 25 nm. The results indicate that electron-electron scattering might be an important source for hot electrons in the next generations of Si-MOSFETs. But the effect decreases if the channel length comes close to 25 nm.

1 Introduction

The correct treatment of electron-electron and electron-impurity scattering is still a challenge for modern semiconductor device simulation [1-3]. A two particle model must be used, making the simulation of the short range electron-electron interaction very expensive within the Monte Carlo approach. On the other hand, electron-electron interaction may be the single most important source of hot electrons in modern short channel Si-MOSFETs with implications for the life-time of these devices.

We introduced the local iterative Monte Carlo (LIMO) algorithm in order to reduce the computation time of Monte Carlo (MC) simulations of rare events like hot electron effects by a more efficient use of the computational resources [4-5]. The LIMO approach gives new possibilities for an effective treatment of electron-electron scattering. Comparison with experimental findings for a 90 nm MOSFET show an excellent agreement when electron-electron scattering is included in the LIMO calculation. We use this new approach to investigate MOSFET scaling trends down to 25 nm channel length.

2 Theory

Two properties of the LIMO algorithm simplify the simulation of electron-electron interaction effects compared to standard MC algorithms. First, the energy distribution of electrons is known at each iteration of the LIMO algorithm. LIMO does not simulate the flight of an ensemble of electrons through the device like standard MC algorithms but changes the distribution iteratively by using information from MC simulations of relatively short electron trajectories ($\sim 10^{-14}$ sec). The electron distribution is always accessible and the self-consistent long range electron-plasmon and short range electron-electron scattering rates can be calculated directly using Fermi's Golden Rule. It is not necessary to perform a time average in order to gain an electron distribution.

Second, the partner electron for a short range electron-electron scattering can be created out of the distribution and then returned to the distribution for each scattering process. The computationally expensive search for a partner electron from the ensemble of simulated electron is therefore not necessary in LIMO. Since the distribution memorizes only the energy and not the complete momentum of the electron, the momentum direction of the partner electron can be chosen arbitrarily and the final direction need not be calculated. This simplifies a correct treatment of energy and momentum of the interacting electrons, compared to standard MC algorithms.

3 Results for short channel MOSFET

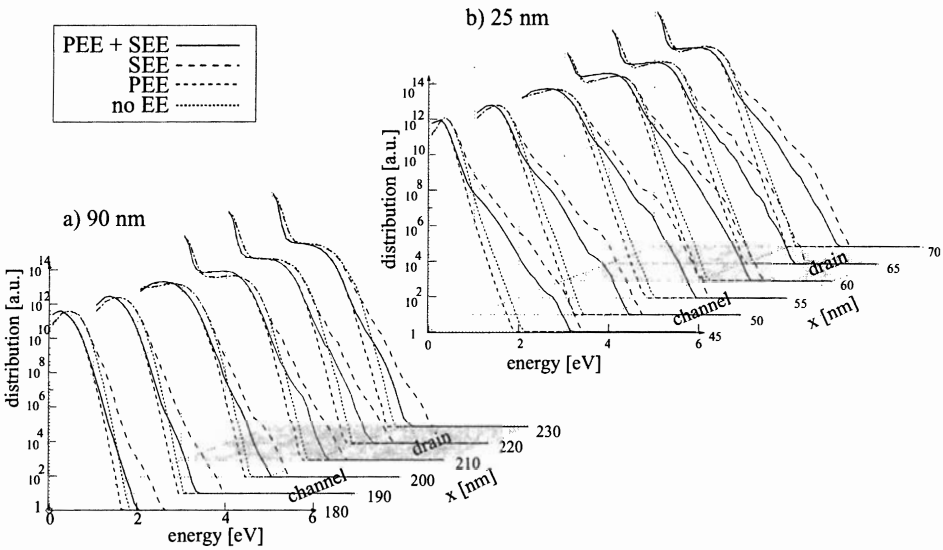

Fig. 1. Influence of electron-electron scattering on the energy distribution of electrons in a 90 nm MOSFET (a) and 25 nm MOSFET (b) with 1.5 V applied to drain and gate. Distributions obtained including no electron-electron scattering (no EE), only electron-plasmon scattering (PEE), only the short range direct interaction (SEE) and the full model (PEE+SEE) are displayed.

The structures from the "well-tempered MOSFET" project (http://www-mtl.mit.edu:80/Well) with channel length 90 nm, 50 nm and 25 nm were used for the investigation of hot electron effects in short channel Si-MOSFETs. Figure 1 shows the influence of electron-electron scattering on the energy distribution of electrons in: (a) 90 nm MOSFET (a), (b) and 25 nm MOSFET, with 1.5 V applied to drain and gate. In both MOSFETs electron-plasmon scattering (PEE) as a relaxation mechanism leads to a reduction of the distribution spread in energy, while the direct short range interaction (SEE) increases the high energy tail. While the 90 nm MOSFET shows only a moderate tail increase due to the short range interaction, the effect simulated in the 25 nm MOSFET is much stronger. Substrate and gate current were calculated from the simulated electron distributions for the analysis of hot electron effects (see [6] for a description of the procedure). Figure 2 compares the resulting currents for the 90 nm MOSFET with measurements. With electron-electron interaction, an excellent agreement could be achieved.

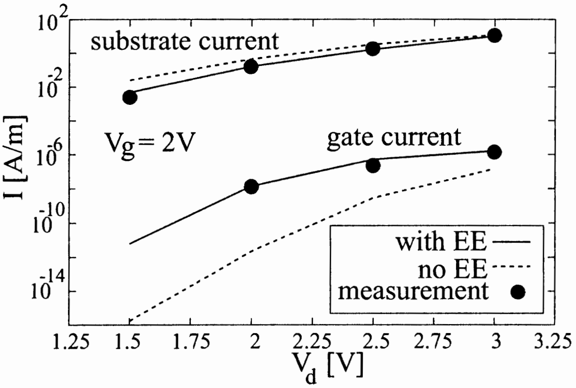

Fig. 2 Substrate current and gate current as function of the drain voltage for the 90 nm Si-MOSFET with a gate voltage of 2 V. Measurement results are compared with the LIMO results calculated with and without electron-electron scattering (EE).

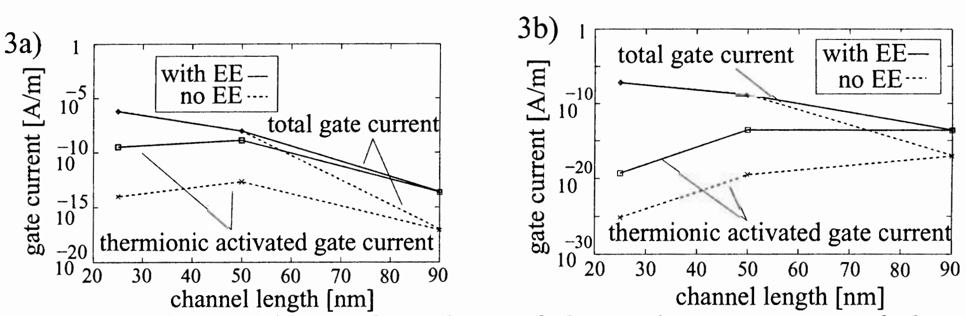

Fig. 3 Channel length dependence of the total gate current and the thermionic emission component of the gate current calculated with and without electron-electron scattering (EE). (3a) shows the results using constant bias scaling with 1.5 V at drain and gate and (3b) the same with quasi constant bias scaling with 1.5 V, 1.1 V and 0.8 V for the 90 nm, 50 nm and 25 nm MOSFET, respectively.

The channel length dependence of the gate current, as a measure for degradation effects, is investigated in Fig. 3 for constant bias scaling (3a) with 1.5 V at drain and gate and quasi constant bias scaling (3b) with 1.5 V, 1.1 V and 0.8 V for the 90 nm, 50 nm and 25 nm MOSFET, respectively. The 90 nm device shows a significant increase of the gate current due to electron-electron scattering. The smaller devices show no effect for both types of scaling, because tunneling of cold electrons at the source is the main contribution to the gate current. Since degradation effects in MOSFETs may be related to hot electrons and not tunneling cold electrons, we plotted the thermionic emission component of the gate current separately. The amount of hot electrons which are heated over the 3.2 eV barrier of the SiO_2 increases significantly, when the channel length is reduced from 90 nm to 50 nm with constant voltage but decreases slightly with a further channel length reduction to 25 nm. In case of the quasi constant bias scaling the amount of hot electrons remains almost the same for a channel length of 50 nm and a voltage of 1.1 V. The amount is significantly reduced by a further decrease of the channel length to 25 nm with 0.8 V at drain and gate. Thus, device degradation due to hot electron effects may remain an important issue for the next generations of MOSFETs but will become less important for ultra small devices with channel length in the range of 25 nm.

4 Conclusion

The LIMO technique was used to investigate the effect of electron-electron scattering on hot electron effects in down-scaled Si-MOSFETs. This approach has some advantages compared to the way electron-electron scattering is treated in standard Monte Carlo algorithms. The results for Si-MOSFETs with channel length down to 25 nm indicate that electron-electron scattering is an important source for hot electrons in small MOSFETs. It may play an important role for the next generations of Si-MOSFETS but we expect less pronounced effects for ultra small MOSFETs with channel length in the 25 nm range.

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