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Hot Carrier Energy Distributions in Short Channel MOSFETs and the Persistence of Substrate Currents at Low Drain Voltages

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With the scaling down of supply voltages hot carrier effects in submicron MOSFETs have been observed which to date have not been satisfactorily explained. For instance, the temperature dependence of the substrate current has been found to be positive, negative or virtually independent, depending on device size and bias condition [1]. Furthermore, substrate currents have been found to persist in devices operating with drain voltages as low as 0.7V, somewhat below the threshold energy of impact ionisation [2]. To understand the origin of hot carrier effects in MOSFETs it is important to model accurately the hot carrier distribution in the channel. A wide variety of modelling techniques are available but most assume that the hot carrier distribution is determined by the channel electric field and phonon scattering. It is known [3], however, that as supply voltages are reduced that the electron energy distribution is strongly affected by the energy supply which, therefore, plays an equally important role in determining hot carrier effects such as impact ionisation and gate currents. When charge carrier scattering is assumed to be dominated by phonon interactions the hot carrier distribution exhibits a transition region close to the supply energy. Well below this energy the energy distribution is determined principally by the electric field whereas well above the supply energy it takes the form of a Boltzmann distribution. with an effective temperature close to the lattice temperature, T. Recently we have shown [4] that the effective temperature of the hot carrier distribution above the supply energy decreases asymptotically from ~1.4 T_L towards T_L. However, when electron-electron interactions are included in the scattering model we have shown [5,6] that the hot carrier population above the supply voltage is substantial increased.

In this paper we show how the form of the hot carrier distribution in the region around the supply energy can be obtained from a hybrid Monte Carlo / iterative solution of the Boltzmann transport equation. The role played by the hot carrier distribution in determining substrate current is described and the underlying physics discussed. We show that the persistence of substrate current at drain voltages below the threshold voltage can be explained by interactions between energetic electrons close to the drain. It is also shown that the hybrid technique can accurately determine the hot carrier distribution when the electron-electron interaction is treated rigorously using an energy band structure based on the **k.p** method.

Figure 1 shows the hot carrier distribution near the drain of a MOSFET operating at three different drain voltages. In the absence of electron-electron interactions the hot carrier distribution at an energy greater than is available from the electric field falls off rapidly as described above. The shape of the distribution in the region of the supply energy is not unique but depends on the energy of the interacting phonon and/or the ambient temperature. The form of the distribution is different, in for example, GaAs where the phonon energy is about half that of silicon. When electron-electron interactions are included the hot carrier distribution is greatly enhanced and increases with drain voltage. Figure 2 shows the substrate current obtained when the electron energy distribution is combined with the impact ionisation soft threshold obtained by Sano [7]. In the absence of electron-electron interactions a measurable substrate current is observed at drain voltages as low as 0.8V at room temperature. However, at 150K negligible substrate current is observed when the supply energy is less than the impact ionisation threshold energy. Our model shows that when electron-electron interactions are included substrate current will be observed at low voltages and low temperatures.

In conclusion, we demonstrate a hybrid Monte Carlo / iterative technique for solving the Boltzmann transport equation and show it can be used to explain the form of the hot carrier distribution in MOSFETs operating at low drain voltages. We also show that electron-electron interactions near the drain of a MOSFET can account for the persistence of substrate current in MOSFETs operating at low drain voltages and low temperatures.

References

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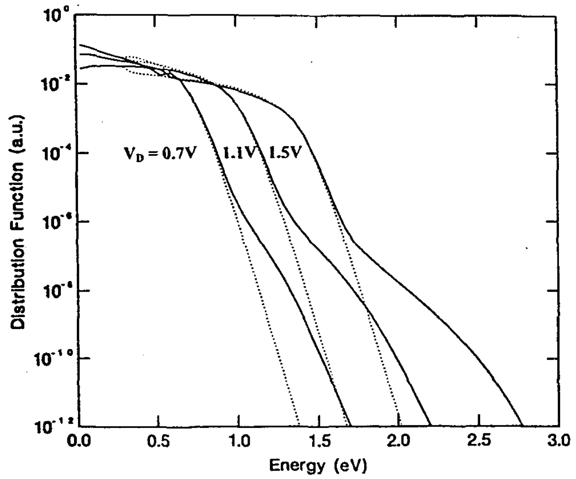

Figure 1. Hot carrier distribution near the drain of a MOSFET at drain voltages of 0.7V, 1.1V and 1.5V. Dotted line: excluding electron-electron scattering; solid line: including electron-electron scattering.

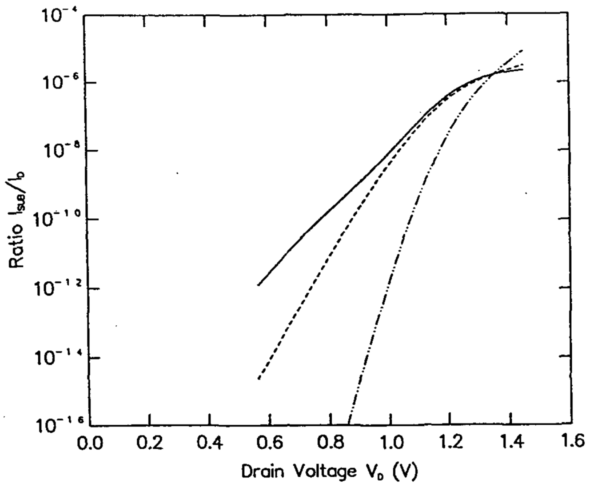

Figure 2. Ratio of substrate current to drain current as a function of drain voltage. Solid line: including electron-electron scattering. Broken lines: excluding electron-electron scattering; dotted line - 300K dot-dashed line 150K.