Study of Cutoff Frequency Calculation in the Subthreshold Regime of Operation of the SOI - MESFETs

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ABSTRACT

We have developed a transport model, based on the solution of the Boltzmann Transport Equation, for modeling *n*-channel silicon-on-insulator MESFETs. All relevant scattering mechanisms for the silicon material system are included in the transport portion of the device simulator. From our simulations we have found that the mobility of the equivalent SOI MESFET device is three to five times higher than that of the SOI MOSFET in the sub-threshold regime. So, the cutoff frequency of the SOI MESFET will be higher than its conventional counter part.

Keywords: low-field mobility, surface-roughness scattering, low-power r.f. applications.

1 INTRODUCTION

Micropower circuits based on sub-threshold MOSFETs are used in a variety of applications ranging from digital watches to medical implants. The principal advantage of a transistor operating in the sub-threshold regime is the minimum power consumption, but the main drawback is its speed. Micropower circuits are limited to operating frequencies below ~ 1MHz due to low cut-off frequency $f_T=\mu V_T/2\pi L_g^2$, where μ is the carrier mobility, $V_T=kT/e$ the thermal voltage and L_g is the gate length. In the sub-threshold regime, it is impractical to increase f_T by reducing the gate length because of difficulties with transistor matching. The only remaining option to increase f_T is to increase the carrier mobility. In a prototypical MOSFET device in the on state, inversion electron mobility is typically 600-700 cm^2/Vs but this falls to only 100-200 cm^2/Vs in weak inversion, and one expects a cut-off frequency in the range between 40 to 80 MHz for a sub-threshold MOSFET with L_g=1 μm. The above discussion suggests that alternate device structures, like the Schottky Junction Transistor (SJT) [1] (or the SOI MESFET architecture), are needed that will satisfy both the low-power and the r.f. requirements and will allow much better operation of, for example, pacemakers. The paper is organized in the following way. In the next section we discuss the methodology of the Monte Carlo technique, with emphasis on the determination of the mobility and on the calculation of the cutoff frequency. In the next section we show our results and, finally, we finish the paper with some conclusive comments.

2 METHODOLOGY: THE MONTE CARLO METHOD

The Monte Carlo model used in the transport portion of the simulator is based on the usual Si band-structure for three-dimensional electrons in a set of non-parabolic Δ-valleys with energy-dependent effective masses. The explicit inclusion of the longitudinal and transverse masses is important and this is done in the program using the Herring-Vogt transformation [2]. Intravalley scattering is limited to acoustic phonons. For the intervalley scattering, we include both *g*- and *f*-phonon processes. The high-energy phonon scattering processes are included via the usual zeroth-order interaction term, and the two low-energy phonons are treated via a first-order process [3]. The first-order process is not really important for low-energy electrons but gives a significant contribution for high-energy electrons. The low-energy phonons are important in achieving a smooth velocity saturation curve, especially at low temperatures. The phonon energies and the coupling constants in our model are determined so that the experimental temperature-dependent mobility and velocity-field characteristics are consistently recovered [4]. In addition to phonon scattering, to properly describe the SOI MESFET devices of interest in this study, we have included surface or interface-roughness scattering in our theoretical model. In the SOI MOSFET device, carriers interact predominantly with the front Si/SiO_2 interface, and in a SOI MESFET device, they interact with the bottom Si/SiO_2 interface. It is a common practice, which we have adopted in this work as well, to include interface-roughness as a real-space scattering event, separated into diffusive and specular type of interaction with an idealized atomically-flat interface. Specular scattering is defined as an elastic deflection by the interface where the momentum perpendicular to the interface is reversed. For the case of diffusive scattering, the deflection angle is chosen at random and utilizes uniform probability density function. In our model, 50% of the interface interactions are treated as specular and 50% as diffusive scattering [5]. Such splitting gives us low field mobility values for the Q2DEG in agreement with the experimental data. Coulomb scattering is generally associated with ionized charges in the bulk and in the SiO_2 layer, and is dominant scattering mechanism at low temperatures. For modeling Coulomb scattering, in this version of the code, we use the Brooks-Herring approach [6]. This approach accounts for the screening effect due to the rest of the mobile charges and makes the scattering potential of a short-range, rather than a long range nature.

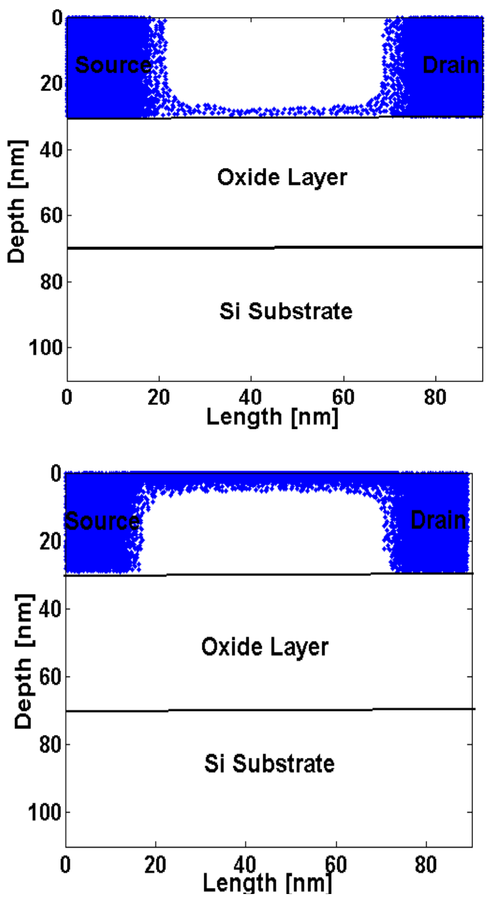

Figure 1: The geometry of the MESFET (top figure) and MOSFET (bottom figure) used in the simulations. Also shown is the electron distribution across the channel.

In solving Poisson's equation, the Ensemble Monte Carlo (EMC) simulation is used to obtain the charge distribution in the device. We use the Successive-Over-Relaxation (SOR) method for the solution of the 2D Poisson equation. The Nearest-Element-Center (NEC) scheme is used as a charge assignment scheme. Within the self-consistent Monte Carlo−2D Poisson equation simulation scheme, modeling of the Schottky barrier is performed using the approach by Cowley *et al.* [7]. In the present version of the code, the Schottky barrier height is taken to be 0.656 eV to represent a $Si/CoSi_2$ material system that is used in the fabrication process of the devices being investigated in this study.

3 RESULTS AND DISCUSSIONS

Since the mobility is the key factor in determining the device cut-off frequency, it is the purpose of this study to calculate the cutoff frequency by investigating the electron mobility improvement of SOI MESFET when compared to SOI MOSFET devices. . To accomplish this goal, we have utilized our in-house Ensemble Monte Carlo device simulator and performed extensive simulations of similar geometry SOI MOSFETs and Si MESFET channels (see Fig. 1).

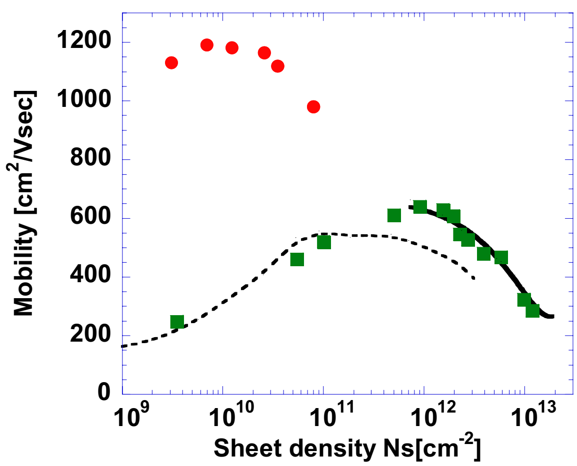

Figure 2: The simulated electron mobility as a function of sheet electron concentration for an SOI MESFET (circles) and an SOI MOSFET (squares). The solid line is the effective mobility measured from an SOI MOSFET with t_{Si} = 21 nm [Ref. 8] and the dashed line is the experimental data from a bulk MOSFET [Ref.9]

To calculate the mobility, we use Monte Carlo device simulations of SOI MOSFET with a gate length of 100 nm, a gate oxide thickness of 4 nm and p-well doping of 3.9×10^{15} cm^{-3}. The model is then applied to a similar gate length SOI MESFET. The results are shown in Fig. 2. For the case of the MOSFET, there exists peak mobility value of ~600 cm^2/Vs at a sheet density of N_s~10^{12} cm^2/Vs but it quickly falls off as N_s is increased or decreased. In contrast to the MOSFET mobility behavior, the electron mobility in the MESFET channel is approximately constant with N_s, with a value in excess of ~1000 cm^2/Vs. The SOI MOSFET mobility we calculate above threshold compares well to measured data from a device with a similar SOI channel thickness [8]. The observed mobility enhancement can be explained in the following manner. In the case of a SOI MOSFET the high electric fields required to form the inversion layer, pull the carriers closer to the rough Si/SiO_2 interface below the MOS gate. In contrast, the perpendicular electric fields within the MESFET are smaller and carrier confinement is less pronounced. Therefore, fewer of the current carrying electrons will interact with the rough back interface, giving rise to higher average electron mobility in the MESFET device. The mobility in the MESFET channel is approximately twice as large as that of the peak MOSFET mobility value, while in sub-threshold regime ($N_s << 10^{11}$ cm^{-2}) it is approximately five times larger. Hence the cutoff frequency based on mobility is 114~126GHz.

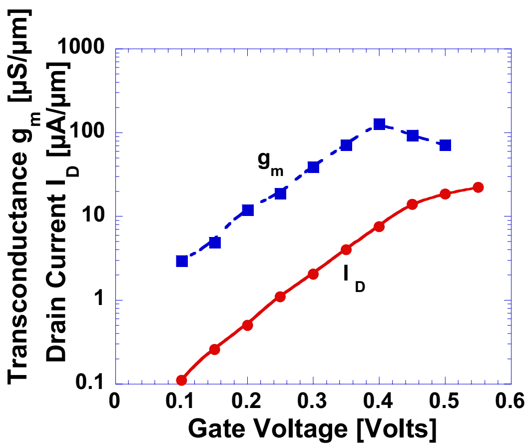

Figure 3: Transfer characteristics and Variation of transconductance with gate voltage.

Another way for the extraction of cutoff frequency is $f_T=g_m/2\pi C_g$, where g_m is the transconductance and C_g is the gate capacitance of the device. To calculate the cutoff frequency we have simulated the transfer characteristics and the transconductance variation with the applied gate bias as shown in Fig. 3. The gate capacitance is also found from the simulation. Now using above formula we have determined the cutoff frequency for the gate length of 50nm. The obtained value is 105GHz as shown in Fig. 4.

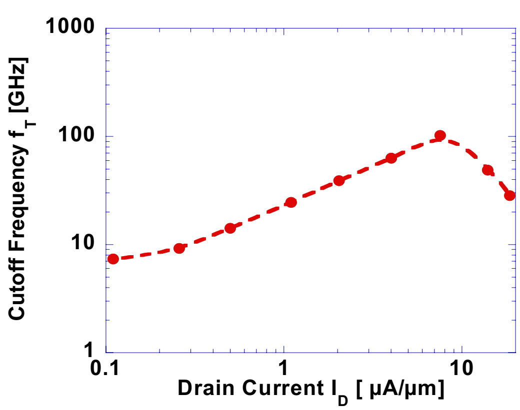

Figure 4: Variation of Cutoff frequency with respect to Drain current.

This cutoff frequency value is quite high with respect to the cutoff frequency of a MOSFET.

4 CONCLUSION

In this work, we have developed a transport model to extract the low field mobility of sub-threshold MESFET. From mobility model, the Monte Carlo device simulation predicts a fivefold increase in the electron mobility of SOI MESFET compared to that for similar geometry SOI MOSFET operating in the sub-threshold regime. Therefore, this device structure for a particular gate length exhibits higher cut-off frequency which is calculated by two different but consistent methods and provides the same range of cutoff frequency. Due to this enhanced cutoff frequency, SOI MESFET is a suitable candidate for application in r.f. micropower circuit design.

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