Sub-Threshold Electron Mobility in SOI MESFET

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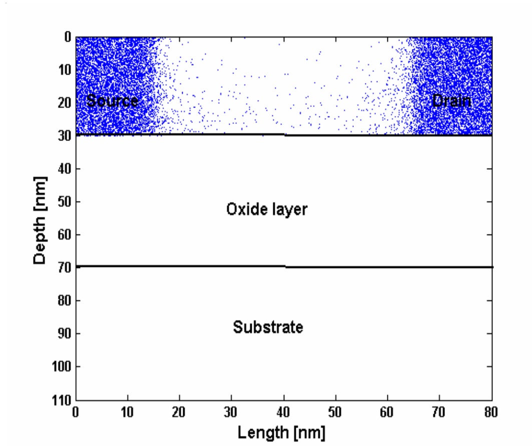
ABSTRACT

Micropower circuits use subthreshold MOSFETs that consume minimal power resulting from the combination of ultra-low drain currents ($10^{-11} < I_d < 10^{-5}$ A/µm) and small drain voltages required for saturation (V_d^{sat} ~150-200mV). Unfortunately, sub-threshold CMOS is a slow technology, with micropower circuits limited to operating frequencies below ~ 1MHz. To achieve higher sub-threshold operating frequencies, we have proposed a Schottky Junction Transistor (SJT) [1] as an alternative to sub-threshold MOSFET devices. It adopts a MESFET architecture and exhibits higher electron mobility. The enhanced MESFET mobility leads to a corresponding increase in the cut-off frequency f_T compared to a similar gate length MOSFET carrying the same amount of current

Keywords: Schottky Junction Transistor (SJT), subthreshold conduction, micropower.

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 sub-threshold transistor operation is the minimal power consumption that results from the combination of ultra-low drain currents ($10^{-11} < I_d < 10^{-5}$ A/µm) and small drain voltages required for saturation (V_d^{sat} ~ 150-200 mV). However, the sub-threshold CMOS is a slow technology, with micropower circuits limited to operating frequencies below ~ 1MHz due to its low cut-off frequency $f_T = \mu V_T/2\pi L_g^2$, where µ is the carrier mobility, $V_T = kT/e$ is 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 MOSFET, the inversion electron mobility is typically 600-700 cm^2/Vs but falls to only 100-200 cm^2/Vs in weak inversion, and we, therefore, expect a cut-off frequency in the range 40-80 MHz for a sub-threshold MOSFET with L_g = 1 µm. To achieve higher sub-threshold operating frequencies we have proposed a Schottky Junction Transistor (SJT) as an alternative sub-threshold device [1] that adopts MESFET architecture. To confirm that the carriers exhibit higher mobility in this device structure, we have performed Monte Carlo simulations of similar geometry MOSFET and MESFET devices (see Fig. 1).



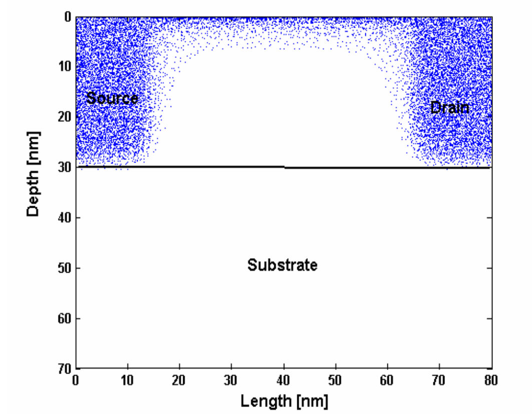


Fig. 1: The geometry of the MESFET (upper figure) and MOSFET (lower figure) used in the simulations. Also shown is the electron distribution across the channel.

2. MOBILITY CALCULATION

Electron mobility is an important parameter as it describes the ease with which carriers respond to applied electric fields. For bulk material systems with low impurity concentration, the mobility is limited by phonon scattering. Coulomb scattering plays an important role if the doping density is in excess of 10^{17} cm^{-3}. In the device structures from Fig. 1, surface-roughness scattering plays significant role at high transverse fields. Thus, for accurate simulation of the output current, modeling of the surface mobility is very important. At low electric fields, the mobility can be found as a ratio of the average particle drift-velocity and the electrical field. Instead of the cell based calculation, we calculate the electron mobility for each particle in the channel using $\mu(x)=v(x)/\bar{E}_x(x)$. An average over time (in the steady state) and space is taken to calculate the average mobility. The method is noisy, but it allows us to investigate the role played by interface-roughness on the electron mobility for devices with different channel thickness.

3. DESCRIPTION OF THE 2D DEVICE SIMULATOR

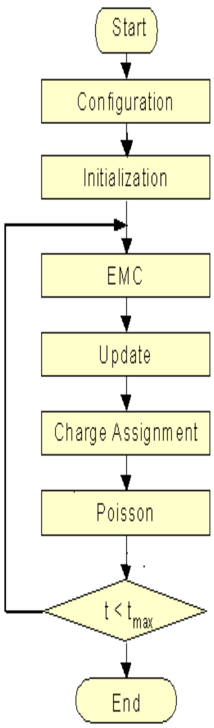


Figure 2: 2D Monte Carlo device simulator.

The 2D ensemble Monte Carlo method, coupled with a 2D Poisson solver, is used for the device simulation. It 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 six conduction band valleys, inherent to the silicon band structure, are included through three pairs. The longitudinal and the transverse masses are very important in this case and they have been included in the model using the Herring-Vogt transformation [2]. It is well known that intra-valley scattering is limited to acoustic phonons, but for inter-valley scattering we have included both *g* and *f*–phonon processes. Coulomb and surface roughness scattering are included in this model as they strongly affect the carrier mobility at low and high electric fields, respectively.

The successive over relaxation (SOR) method has been used for the solution of the 2D Poisson equation and the Monte Carlo simulation has been used to obtain the charge distribution in the device. Within a Monte Carlo scheme, the charges are distributed within a continuum mesh instead of discrete grid points. The particle mesh coupling is used to perform the switch between the continuum in a cell and discrete grid points at the corners of the cell. The charge assignment has been carried out using the Nearest-Element-Center (NEC) method [3,4]. This method leads to zero self-force for non-uniform meshes and spatially varying dielectric constants. The flow chart of the Monte Carlo device simulator is shown in Fig. 2.

4. RESULTS AND DISCUSSION

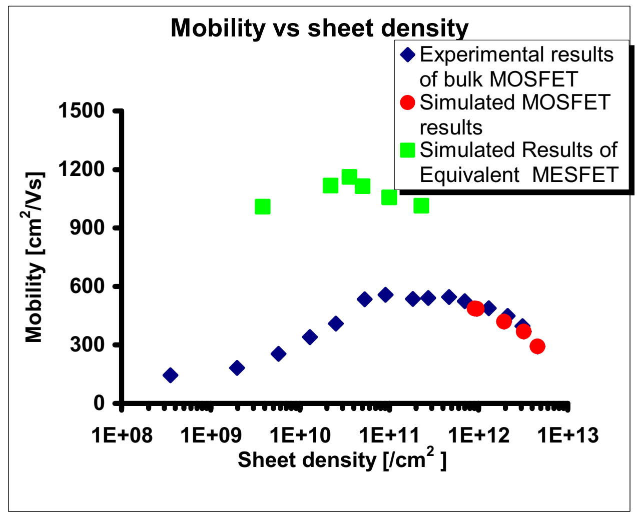


Figure 3: Mobility vs. sheet density.

In Fig. 3 we show the variation of SOI MESFET mobility and the MOSFET mobility with sheet density. It is seen that at high sheet density the mobility degrades quickly due to surface-roughness scattering. For the case of a MOSFET device, there exists a peak mobility value of ~600 cm^2/Vs at a sheet density of N_s~10^{12} cm^2/V-s but this quickly falls off as N_s is reduced below 10^{10} cm^{-2}, corresponding to the sub-threshold regime of weak inversion. In contrast, the electron mobility in the MESFET channel has a higher peak value of 1200cm^2/V-s and does fall down with decreasing N_s, but its magnitude is larger than the MOSFET mobility. The same is true for higher sheet charge densities. This behavior can be explained by the different role played by surface-roughness scattering. In the case of a MOSFET, the stronger electric field pulls the carriers closer to the surface. In MESFETs, it pulls carriers away from the interface. As seen from Fig. 1, the current flow in the MESFET device is away from the upper interface when compared to the MOSFET device. As a result of this, fewer current carrying electrons interact with the rough interface and the average mobility is increased. Of course, as the thickness of the MESFET channel is reduced, a greater fraction of the electrons are forced to interact with the back interface and the average mobility will degrade. This behavior is shown in Fig. 4. Also note, by comparing the results shown in Fig. 3, that the MOSFET mobility follows the experimental values [5] and the MESFET mobility is 5 to 10 times higher than that of the MOSFET device. The enhanced MESFET mobility will lead to a corresponding increase in the cut-off frequency f_T compared to a similar gate length MOSFET carrying the same amount of current.

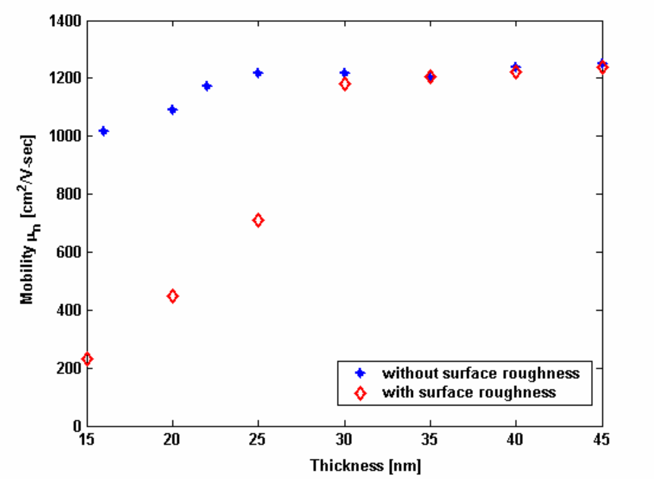


Figure 4: Mobility vs. silicon thickness with and without surface roughness scattering.

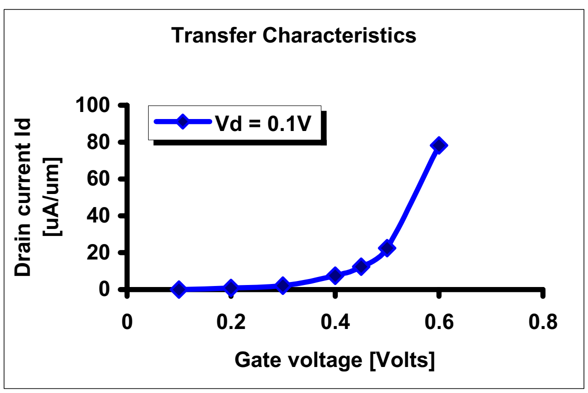


Figure 5: Transfer characteristics to calculate f_T

From the transfer characteristics of the MESFET device shown in Fig. 5 for drain voltage $V_d = 0.1$V, we calculate the transconductance g_m, which is given by

$$g_m = \left(\frac{\partial I_D}{\partial V_g}\right)_{V_d = constant} = 40\mu S/\mu m\,.$$

The gate capacitance C_{gs} equals to

$$C_{gs} = \left(\frac{\partial Q}{\partial V_g}\right)_{V_d = constant} = 1.47\text{x}10^{-13}\ \text{F/cm},$$

thus leading to a cut off frequency of

$$f_T = \frac{1}{2\pi}\frac{g_m}{C_{gs}} = 433\ \text{GHz}.$$

CONCLUSIONS

In this work we have utilized 2D Monte Carlo device simulator to successfully simulate Silicon MESFETs operating in the subthreshold regime that exhibit high cutoff frequency. The enhancement in the cut-off frequency is due to increased electron mobility and decreased capacitance of the structure, making it suitable for r.f. micropower circuit applications.

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REFERENCE

[1] T. J. Thornton "Physics and Applications of the Schottky Junction Transistor" *IEEE Trans. Electron Devices* 48, 2421 (2001)

[2] C. Herring and E. Vogt, "Transport and Deformation-Potential Theory for Many-Valley Semiconductors with Anisotropic Scattering", *Phys. Rev*. 101, 944 (1956).

[3] C. Jacoboni and L. Reggiani, "The Monte Carlo Method for the Solution of Charge Transport in Semiconductors with Applications to Covalent Materials", *Rev. Modern Phys.* 55, 645 (1983).

[4] R. W. Hockney and J. W. Eastwood, *Computer Simulation Using Particles*. Maidenhead, U.K. McGraw-Hill, 1981

[5] J. T. C. Chen and R. S. Muller, "Carrier mobilities at weakly inverted silicon surfaces," *J. App. Phys.* 45, 828 (1974).