Using a First Principles Coulomb Scattering Mobility Model for 4H-SiC MOSFET Device Simulation

S. Potbhare¹, a, G. Pennington¹, N. Goldsman¹,b, A. Lelis², D. Habersat², F. B. McLean³ and J. M. McGarrity³

¹Department of Electrical Engineering, University of Maryland, College Park, MD 20742, USA
²U.S. Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783, USA
³Berkeley Research Association, Springfield, VA 22150, USA

¹apotbhare@umd.edu, bneil@umd.edu

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Abstract. A physics based device simulator for detailed numerical analysis of 4H-SiC MOSFETs with an advanced mobility model that accounts for the effects of bulk and surface phonons, surface roughness and Coulomb scattering by occupied interface traps and fixed oxide charges, has been developed. A first principles quasi-2D Coulomb scattering mobility model specifically for SiC MOSFETs has been formulated. Using this, we have been able to extract the interface trap density of states profile for 4H-SiC MOSFETs and have shown that at room temperature, Coulomb scattering controls the total mobility close to the interface. High temperature, low field simulations and experiments show that the current increases with increase in temperature. The effect of Coulomb scattering decreases with increase in temperature causing an increase in the total mobility near the interface at low gate voltages.

Introduction

Unusually high interface trap densities pose the biggest challenge to SiC MOSFET device operation. Developing a density profile for the interface traps and predicting their effect on device operation will help manufacturers to refine their process and produce better SiC devices. We have developed an advanced drift diffusion device simulator to analyze the physics that goes on inside a SiC MOSFET. A key and unique aspect of this simulator is a sophisticated mobility model that accounts for the effects of bulk and surface phonons, surface roughness, and Coulomb scattering of mobile carriers by occupied interface states and fixed oxide charges. The first principles Coulomb scattering mobility model developed for SiC MOSFETs [1] incorporates the scattering effects due to occupied traps and fixed charges, distribution of mobile charges inside the semiconductor, distribution of traps and fixed charges inside the oxide, screening of traps by mobile carriers and temperature. Simulations show that Coulomb scattering is the dominant mobility limiting mechanism in 4H-SiC MOSFETs close to the interface, giving surface mobilities for electrons as low as 20 cm²/Vs – 30 cm²/Vs at room temperature. A few nanometers away from the interface, the Coulombic interaction between occupied traps and mobile carriers is greatly reduced, and other scattering mechanisms largely control the total mobility. Room temperature simulations of ID-VGS curves and comparisons with experimental data enable us to extract the energy dependent interface trap density of states profile for the 4H-SiC MOSFET [1]. The extracted profile, shown in Fig. 1, shows a constant density of states in the middle of the bandgap and an exponential rise near the band edges, and is similar to experimental measurements reported in literature [2 - 5].

One notable property of many experimental 4H-SiC MOSFETs is that the current rises with increase in temperature. With increase in temperature, electrons (and holes) gain more energy and hence are trapped less. This reduction in the occupied interface trap density causes an increase in the Coulomb mobility near the interface. Also, the reduction in trapped charge causes an increase in the amount of free charge in the inversion layer that is available for conduction. These two effects give an increase in current with temperature.

4H-SiC Mobility Model

The total low field mobility is a combination of bulk phonon, surface phonon, surface roughness and Coulomb mobilities. The extremely high density of interface traps in 4H-SiC MOSFETs...
required the development of an advanced Coulomb scattering mobility model. As the effect of Coulomb scattering decreases with increasing distance from the interface, the Coulomb mobility was required to have a depth-dependence. As the traps are screened by the mobile electrons, it was necessary to devise a screened Coulomb scattering mobility model.

a) Quasi 2D Coulomb Mobility Model: The screened Coulomb potential function given by (1) is used to calculate the scattering rate using Fermi Golden Rule.

\[ V(r) = \frac{e^2}{4\pi\varepsilon} \frac{1}{r} e^{-q_{sc} r} \]  

(1)

where, \( \varepsilon = (\varepsilon_{SiC} + \varepsilon_{SiO_2})/2 \cdot q_{sc} \) is the screening wavevector given by:

\[ q_{sc} = \sqrt{\frac{e^2 N_{inv}}{\varepsilon_{SiC} Z_{av} T_k}} \]  

(2)

where, \( N_{inv} \) is the inversion layer charge density and \( Z_{av} \) is the average depth of the inversion layer.

The screened Coulomb scattering mobility as a function of depth obtained from the Fermi Golden Rule is given as [1]:

\[ \frac{1}{\mu_c(z, z_i, T_e)} = \frac{m^* e^2 N_{2D}(z_i)}{16\pi^2 h^2 k_B T_e} F(z, z_i, T_e) \]  

(3)

where \( N_{2D}(z_i) \) is the sum of occupied interface traps and fixed oxide charge at a depth \( z_i \) inside the oxide. \( z \) is the distance of the mobile charge from the interface.

Effect of screening and depth-dependence of Coulomb mobility is given by:

\[ F(z, z_i, T_e) = \int_{-\infty}^{\frac{z_i}{2}} \left[ \frac{1}{1 + \frac{8 m^* k_B T_e}{\hbar^2} \sin^2 \alpha + \frac{q_{sc}^2}{h^2} (z - z_i)} \right] \exp \left[ -2 \frac{8 m^* k_B T_e}{\hbar^2} \sin \alpha + \frac{q_{sc}^2}{h^2} (z - z_i) \right] d\alpha \]  

(4)

Our method of treating Coulomb scattering as a quasi-2D phenomenon gives us a Coulomb mobility for a mobile charge at any location inside the semiconductor. This can be directly incorporated in the device simulator. Similar results were obtained by previous investigators using analytical approximations and did not provide a form suitable for device simulation [6, 7].

The Coulomb mobility (Eqn. (3)) is directly proportional to temperature. Also, with increase in temperature, the density of occupied interface traps decreases, leading to a further improvement in Coulomb mobility. Increase in temperature also increases the amount of inversion charge which increases screening leading to increase in Coulomb mobility. Thus for 4H-SiC MOSFETs, near the interface, Coulomb mobility increases with increase in temperature.

b) Surface Roughness Mobility Model: Scattering of mobile charges due to the roughness of the SiC/SiO₂ interface is the second most important scattering mechanism in 4H-SiC MOSFETs. Surface roughness mobility is modeled as inversely proportional to the square of the component of the electric field that is perpendicular to the interface [8]. Hence, surface roughness mobility decreases with increase in gate voltage, making it important at higher gate voltages.

\[ \mu_{SR} = \frac{\Gamma_{SR}}{E_{\perp}^2} \]  

(5)

The parameter \( \Gamma_{SR} \) depends on the roughness properties of the SiC/SiO₂ interface. We have included a weak dependence on temperature for this parameter for 4H-SiC MOSFETs. With increase in temperature, the surface becomes slightly smoother, resulting in a small increase in surface roughness mobility for a constant perpendicular field.

\[ \Gamma_{SR}(T) = \Gamma_{SR}(300) \left( \frac{T}{300} \right)^{\frac{d_{SR}}{300}} \]  

(6)

Even though \( \Gamma_{SR} \) increases with temperature, increase in charge density with temperature causes an increase in the perpendicular field, leading to a net decrease in surface roughness mobility.
Comparisons of simulated and experimental $I_d$-$V_G$ curves at different temperatures give the values of $\Gamma_{SR}(300)$ and $\alpha_{SR}$ as $3.7 \times 10^{12}$ V/s and 1.65 respectively. Screening by inversion layer charges has not been considered for surface roughness scattering, and so we might be overestimating the effect of surface roughness.

c) **Total Mobility:** In addition to the two mobilities described above, the total low field mobility depends on the bulk phonon and the surface phonon mobilities [8]. Both these mobilities decrease with increase in temperature. Hence, eventually, at high temperatures, surface phonon and bulk phonon scattering will limit the total mobility and reduce the current with increase in temperature.

**Occupied Interface Trap Density and Inversion Charge Density**
For a 200°C increase from room temperature, the intrinsic carrier concentration for 4H-SiC increases by a factor of $10^{11}$ causing a rapid rise in charge concentration at a given bias. Moreover, as the mobile carriers gain more energy, they are trapped less, causing a reduction in occupied interface trap density. Hence, more carriers are available for conduction. A comparison of inversion charge density and occupied interface trap density at different temperatures for an $n$-channel 4H-SiC MOSFET is shown in Fig. 2. Notice the increase in inversion charge density and reduction in occupied interface trap density with rise in temperature. The combination of increase in mobility and mobile carrier concentration gives increase in current with temperature in 4H-SiC MOSFETs.
Simulation Results

Agreement of $I_D-V_{GS}$ simulations with experiment at different temperatures is shown in Fig. 3. Comparison of simulated and experimentally measured IV data gives us an estimate for the interface trap density of states (Fig. 1) and for the surface roughness mobility parameters.

Due to large amount of scattering at the surface, the maximum current flows some distance inside the semiconductor as shown in Fig. 4. The peak of the current density curve shifts towards the interface with increase in gate voltage. With increase in temperature, the rise in current density at all depths is clearly seen, indicating that the total current increases with increase in temperature. As shown in Fig. 5, at low gate voltages, when Coulomb mobility dominates, the total mobility close to the interface increases with increase in temperature. Whereas, at high gate voltages, and deeper inside the bulk, the total mobility decreases with increase in temperature due to the effect of surface roughness and phonon scattering. But because of the increase in carrier concentration, the total effect is of an increase in current with temperature everywhere in the device.

Conclusion

A comprehensive temperature dependent mobility model for 4H-SiC MOSFETs has been presented and simulation results have been verified by comparison with experiments. Coulomb scattering by occupied interface traps and fixed oxide charges is the main cause of low surface mobilities in 4H-SiC MOSFETs. With increase in temperature, the current in the device increases due to improvement in surface mobility and due to the increase in mobile carrier concentration.

References
