A Monte Carlo study on electron mobility in quantized cubic silicon carbide inversion layers

F. Gámiz, a) J. B. Roldán, and J. A. López-Villanueva
Departamento de Electrónica y Tecnología de Computadores, Universidad de Granada, Facultad de Ciencias, Avd. Fuentenueva s/n, 18071 Granada, Spain

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Electron transport properties in cubic silicon carbide (β-SiC) quantized inversion layers have been studied and the results of electron mobility calculations at room and higher temperatures have been reported. To do so, we have developed a Monte Carlo simulator used in conjunction with the self-consistent solution of the Poisson and Schroedinger equations. We show that for a fixed inversion charge concentration, β-SiC inversion layer electrons spread less into the bulk than Si ones as a consequence of the effective mass values. Therefore, the defects of the SiO$_2$/β-SiC (interface roughness, charged centers) will strongly affect electron transport properties. We present simulated mobility curves for quantized β-SiC inversion layers taking into account different scattering mechanisms which are then compared to Si mobility curves. Special attention has been paid to the effect of Coulomb scattering due to both interface- and oxide-trapped charges. Mobility curves obtained for different interface-trapped charge concentrations show that electrons in silicon carbide inversion layers are more affected by surface defects at room and higher temperatures than they are in silicon inversion layers. © 1997 American Institute of Physics.

I. INTRODUCTION

Cubic silicon carbide (β-SiC) has been suggested as an appropriate candidate for electronic applications requiring elevated temperature operation, large power voltage capability, low leakage current, and high frequency response. In such operational fields, SiC, like other wide bandgap semiconductors, has important advantages compared to normal semiconductors: (i) The high Si–C bonding energy in silicon carbide makes it resistant to high temperatures and radiation, and endows it with mechanical strength and chemical stability. (ii) The thermal conductivity of SiC (4.9 W cm$^{-1}$ K$^{-1}$) is much greater than in Si (1.5 W cm$^{-1}$ K$^{-1}$), which gives an advantage to SiC in high power amplifiers and lasers. (iii) The wider bandgap of SiC makes the thermal leakage current ten orders of magnitude lower than in silicon. (iv) In addition, the wide bandgap facilitates the use of this semiconductor at much higher temperatures than silicon, since the intrinsic carrier concentration does not exceed $10^{14}$ cm$^{-3}$ at 1100 K in β-SiC. (v) SiC is superior to common semiconductors in possessing an avalanche breakdown field one order of magnitude higher. (vi) SiC also shows a lower relative dielectric constant than silicon, which also offers advantages in applications where parasitic capacitance needs to be controlled. (vii) Another important advantage is a greater saturated electron velocity, making SiC a prime contender for millimeter wave amplifiers. (viii) Finally, the wide bandgap in SiC means this semiconductor is efficient in the manufacture of optoelectronic devices (light emitting diodes covering the entire visible spectrum and photodiodes for the ultraviolet).

Although much work remains to be done in the SiC technology field in order to obtain a commercial production standard, the feasibility of SiC devices has already been shown. Both bipolar and field effect transistors have been successfully manufactured. Good operation at high temperatures and high frequencies has been reported. Both p-n and Schottky diodes with sharp breakdown and low reverse current up to high temperatures have been reported by various groups. Other devices, such as SiC light emitting diodes, and SiC photodiodes and rectifiers have also been reported.

Switching devices, of all the ones mentioned, constitute the largest current area in device activity. By far, the largest effort has concentrated on unipolar devices, that is to say, junction field effect transistors (JFETs), metal-oxide-semiconductor field-effect transistor (MOSFETs), and metal-semiconductor field-effect transistor (MESFETs). Interest in SiC field-effect transistors as a type of device in which drift important is due to high values of the avalanche breakdown field and to high saturation values of the electron drift velocity, which should provide very significant enhancements in transconductance and, therefore, in device speed. Si MOSFETs dominate switching applications, but it is in the high power, high temperature, and high frequency range where SiC MOSFETs are expected to dominate.

Recent advances in crystal growth and thin film epitaxy have allowed the development of high quality single crystals of different SiC polytypes, including β-SiC. Capacitance and conductance studies have revealed that good SiC/SiO$_2$ interface properties can be achieved with thermally grown oxides. Using MOS conductance and capacitance techniques, the interface states at the β-SiC have been characterized by Chaudhry. This researcher found that the electrical properties of the β-SiC/SiO$_2$ system are similar to those of the Si/SiO$_2$ system, and that the thermal oxide of β-SiC is a suitable insulator for fabricating MOS devices on β-SiC. The fabrication of high temperature MOSFETs has already been demonstrated. Shibahara et al. have fabricated inver-

a) Electronic mail: paco@gcd.ugr.es
sion mode MOSFETs in β-SiC films on Si(100) substrates. Palmour et al. characterized the current-voltage characteristics of β-SiC MOSFETs in both inversion and depletion modes. They observed stable transistor action in both types of devices at temperatures up to 823 K, with the depletion mode devices operating very well up to 923 K.

As a consequence of this interest, theoretical analyses and simulations on the electronic properties of silicon carbide and SiC MOSFETs have begun to appear in the last few years. Calculations of high field electron drift velocity behavior were first performed by Ferry, based on the balance equation method. Numerical simulations of nanoscale β-SiC MESFETs have also been carried out. Joshi et al. reported simulation results of field- and temperature-dependent electronic conductivity in β-SiC.

Up to now, numerical simulations related to the electron transport properties of silicon carbide inversion layers have not considered electron quantization. The wide experience obtained in silicon and other semiconductor inversion layers over many years suggests that, for a complete evaluation of the performance potential of silicon carbide MOSFETs, a detailed analysis of the transport properties of quantized silicon carbide inversion layers is essential. Ouisse has already provided numerical results of the self-consistent solution of the Poisson and Schroedinger equations in silicon carbide inversion layers. Nevertheless, no study on the electron transport has been performed. Such a study is presented in this work using a one electron Monte Carlo simulation, focusing our attention on the evaluation of the stationary drift velocity and the low field mobility both at room and higher temperatures. Electron quantization in the inversion layer has been properly taken into account. To do so, the Poisson and Schroedinger equations have been self-consistently solved assuming a simple nonparabolic band model for the SiC. In addition, phonon, surface roughness, and Coulomb scattering due to both bulk impurities and interface-trapped and oxide-trapped charges have been taken into account. We have considered acoustic deformation potential scattering, polar-optical phonon interactions, and intervalley phonon events. In order to incorporate the effect of Coulomb scattering in quantized inversion layers we have adopted a comprehensive scattering model that includes the effects of the oxide-trapped and interface-trapped charge space correlation.

Some results concerning electron mobility in SiC have been briefly presented in Ref. 18. In the current article we study these results in depth and provide a much more detailed physical explanation of mobility behavior. In Sec. II, a short description of the algorithm used to solve the Poisson and Schroedinger equations is given. From the solution of the Poisson and Schroedinger equations, some results concerning the electrical properties of β-SiC inversion layers are also presented, and a discussion about the effect that these properties have on the electron transport is reported in this section. The Monte Carlo simulator used to study the electron transport properties in silicon carbide inversion layers is described in Sec. III (Ref. 19 and 20). Section IV is devoted to the study of the low field electron mobility. The effect that the different scattering mechanisms have on the electron mobility will be carefully analyzed. In particular, the effect of the charged centers (both bulk impurities and interface-trapped and oxide-trapped charges) will also be studied. Finally, several conclusions will be drawn.

II. SUBBAND STRUCTURE

In order to obtain reasonable results in any device simulation, a realistic band structure of the semiconductor used has to be considered. Nevertheless, in the case of a Monte Carlo simulation of the electron transport in semiconductor inversion layers, the numerical difficulties involved in the evaluation of the quantized levels, density of states (DOS), and scattering rates make the utilization of a full band structure an impossible task. Therefore, several crude approximations, such as parabolic and nonparabolic energy-band-dispersion relationships have to be taken into account. Nevertheless, Fischetti et al. have shown that if the electron energy is low enough, a nonparabolic model gives a very good approximation of the results obtained using realistic full band structure models. In the simulations we have performed, the kinetic electron energy is always below 0.5 eV. Therefore, in accordance with the above comments, a simplified nonparabolic description of the silicon band structure is justified. (Ref. 24.)

In a quantized quasi-two-dimensional (Q2D) electron gas, the total energy of one electron in the n-th subband can be written as:

$$E^{(n)} = E_z^{(n)} + E_{\parallel}$$

(1)

where $E_z^{(n)}$ is the energy level of the subband and $E_{\parallel}$ the parallel energy of the electron. The relationship between $E_{\parallel}$ and the parallel wavevector is:

$$E_{\parallel}(1 + \alpha E_{\parallel}) = \frac{\hbar^2}{2} \left( \frac{k_x^2}{m_x} + \frac{k_y^2}{m_y} \right)$$

(2)

where $\alpha$ is the nonparabolicity parameter and $m_x, m_y$ are the components of the diagonal effective mass tensor in the plane parallel to the interface.

To obtain the electron energy levels $E_z^{(n)}$ in a silicon carbide inversion layer in the nonparabolic approximation, we have solved a modified Schroedinger equation that directly includes nonparabolicity, thus directly obtaining nonparabolic solutions:

$$\frac{1}{2\alpha} \sum_{l=1}^{\infty} \left( \frac{\hbar^2}{2m_z(1 + 2GA)} \right)^l d^l \frac{d^l}{dz^l} \frac{d^l E_z^{(n)}(z)}{dz^l} + V(z) \xi_n(z) = E_z^{(n)} \xi_n(z)$$

(3)

$\xi_n(z)$ being the envelope function in the n-th subband, and $V(z)$ the potential well. Alternative approaches to take nonparabolicity into account can be found in the literature. The development of the modified Schroedinger equation used here, the associated boundary conditions, and the application to the calculation of the energy levels in an infinite and a finite quantum square well can be found elsewhere. With this equation, the transverse energy levels can be obtained by using an effective mass which is independent of the transverse energy. However, there is a dependence of these energy levels on the parallel energy, $E_{\parallel}(E_z)$. In a
first-order approximation, we have neglected this dependence of the energy levels on the parallel energy, since we are going to study low electric field electron transport properties. Despite this, we have studied the validity of this assumption. To do so, the dependence of $E_z^{(n)}$ on $E_{||}$ has been considered in our Monte Carlo simulator. We have observed that for the $E_1$ range considered in this study, the effect of this dependence of $E_z^{(n)}$ on $E_{||}$ in the electron transport properties is completely negligible, while the simulation time is significantly longer.

The modified Schroedinger equation (Expression 3) has been applied to the case of a SiC inversion layer using the formalism of step potentials. In the nonparabolic model, the density-of-states DOS of a two-dimensional electron gas can also be easily evaluated according to the following analytical expression:

$$D_n(E) = D [1 + 2\alpha(E - V_n)],$$

(4)

$D$ being the density of states of a parabolic two-dimensional electron gas

$$D = \frac{\sqrt{m_x m_y}}{\pi \hbar^2}$$

(5)

and where

$$V_n = \int_{-\infty}^{+\infty} \xi_n^*(z) V(z) \xi_n(z).$$

(6)

As can be seen, when nonparabolicity effects are included, the density of states in a two-dimensional electron gas becomes dependent on the electron energy.

The band structure of $\beta$-SiC is similar to that of silicon, that is to say, conduction band minima along the $\Gamma X$ direction in the Brillouin zone. However, unlike silicon, the minima are located right at $X$ points in the case of $\beta$-SiC, and therefore, the total valley degeneracy is $n_v = 3$, instead of $n_v = 6$ for silicon. As in silicon, the valleys around the conduction band minimum are assumed to be revolution ellipsoids with a principal axis equal to $m_l$ in the $\Delta$ direction (revolution axis) and with a secondary axis equal to $m_t$. Therefore, for a $\beta$-SiC/SiO$_2$ interface parallel to a [100] plane (the case considered here), if an electric field is applied perpendicular to the interface, the degeneracy of the three equivalent minima of the conduction band breaks and the electrons are distributed in two sets of subbands (as occurs in silicon). One set (unprimed subbands) arises from the valley showing the longitudinal effective mass in the $\Delta$ direction ($E_0, E_1, \cdots$) and the other one (primed subbands) from the two valleys showing the transverse effective mass in the same direction ($E'_0, E'_1, \cdots$). The electron effective masses are assumed to be the ones obtained from cyclotron resonance data, and, for the sake of comparison, are shown in Table I beside the silicon effective masses. To obtain the energy level of each electrical subband, the modified Schroedinger (Expression 3) and Poisson equations are self-consistently solved for each gate voltage value. In this work, we have only considered the contributions of the depletion and inversion charge to the Poisson equation, neglecting the contributions of the image and exchange-correlation potential effects.

To accurately take into account the electron inversion layer population, a model for the quantized inversion layer based on the union of a Q2D electron gas contained in six subbands and a three-dimensional electron gas distributed in a continuum of energy levels is used.

Figure 1 shows the average distance of the inversion layer electrons to the interface $z_{av}$ versus the inversion-charge concentration $N_{av}$ at room temperature. We have considered a $\beta$-SiC/SiO$_2$ structure with an oxide thickness of $t_{ox} = 150$ Å and a substrate impurity concentration of $N_A = 1 \times 10^{16}$ cm$^{-3}$. An aluminum gate has been assumed. As can be seen, $z_{av}$ is larger in Si than in $\beta$-SiC. This fact can be explained by taking into account the effective mass values both in silicon and in $\beta$-SiC. As shown in Table 1, $m_l$ in silicon is larger in silicon than in $\beta$-SiC. Therefore, for a fixed value of the transverse effective field, the unprimed energy levels are lower in Si than in $\beta$-SiC, and as a consequence the Si unprimed subbands spread into the bulk to a lesser extent than in the $\beta$-SiC case. In contrast, $m_l$ is smaller in silicon than in $\beta$-SiC, and therefore Si primed energy levels are higher, and the Si primed subbands spread into the bulk to a greater extent than their $\beta$-SiC counterparts. This fact can be observed in Fig. 2, where the average penetration of the ground subbands of the two sets, $z_{av}$, both for Si (dashed line) and for $\beta$-SiC (solid line) are shown. In addition, for the same reason ($m_{\beta\text{-SiC}} > m_{Si}$ and $m_{\beta\text{-SiC}} < m_{Si}$), the energy separation between the ground subbands of both subband ladders is smaller in $\beta$-SiC, and as a consequence the relative

| TABLE I. Effective mass values for both $\beta$-SiC and Si. |
|-------------|-------------|-------------|
|             | $m_l$       | $m_t$       |
| $\beta$-SiC | 0.247       | 0.667       |
| Si          | 0.19        | 0.98        |

FIG. 1. Average distance of the inversion layer electrons to the interface vs the inversion charge concentration at room temperature for both $\beta$-SiC (solid line) and Si (dashed line).
population of the primed ground subband is bigger. This means that the contribution of the 0' subband to the electric properties of the whole electron gas is much more important in SiC. Apart from that, the lower dielectric constant and the larger bandgap in SiC make the depletion charge higher and therefore, for a given value of \( N_{\text{inv}} \), the transverse electric field near the interface will be bigger, \( z_{\text{av}} \) thus being smaller. At low values of \( N_{\text{inv}} \), the relative population of the 0' subband is maximized and therefore the difference between Si and SiC is also maximized, as shown in Fig. 1.

It is important to note that at low temperatures the population of primed subbands is greatly reduced, and therefore the 0 subband (unprimed ground subband) will control the electron transport properties of the whole electron gas. Therefore, the opposite behavior is observed in the electron transport properties of the whole electron gas.

III. MONTE CARLO SIMULATION

Once the actual potential distribution, transverse effective field, and inversion- and depletion-charge concentrations in the structure have been calculated, the effect of a constant electric field \( \epsilon_0 \) applied parallel to the interface is considered. This longitudinal electric field causes the inversion layer electrons to drift in the direction parallel to the interface, undergoing different scattering mechanisms.

The electron dynamic is simulated by the one electron Monte Carlo method, described elsewhere.\(^ {17,19,20} \) To do so, the trajectory of one electron motion is followed for a long period. For each longitudinal electric field value, the average drift velocity is calculated from the history of the electron motion. The simulation begins with an electron in a given subband and with a wavevector \( \mathbf{k}_0 \). The longitudinal-electric field modifies the electron wavevector according to the semiclassical model during a free flight whose length is calculated as usual, taking into account the total scattering rate. The fast self-scattering procedure has been used.\(^ {33} \) The semiclassical model has been appropriately modified to include the nonparabolicity of the conduction band in the electron dynamics. The average drift velocity \( v_{\text{drift}} \) is calculated in this way for several values of the longitudinal electric field, and the low electric field mobility \( \mu_{\text{eff}} \) is obtained from the expression \( v_{\text{drift}} = \mu_{\text{eff}} E \).

In our Monte Carlo procedure we have allowed the electron to travel in six subbands and to move between them. Phonon, surface-roughness, and Coulomb scattering due to both bulk impurities and interface-trapped and oxide-trapped charges have been taken into account. The approach in which the above scattering mechanisms have been considered and the procedure to evaluate the scattering rates are identical with those used previously,\(^ {17,19,20,34} \) except for the inclusion of nonparabolicity. We have considered acoustic deformation potential scattering, polar-optical phonon interactions, and intervalley phonon events. The coupling constants for the intervalley phonons and the acoustic deformation potential were the same in Ferry et al.\(^ {7,14} \) The phonon-scattering rates for inversion layers have been deduced by using Price’s formulation.\(^ {35} \) Surface-roughness scattering has been considered in Ando’s approach with a Gaussian model dependent on the spectral distribution of roughness at the interface.\(^ {28} \) This Gaussian model has been widely used in the literature, although it has been proved that other models (with perhaps a greater physics ground), such as the exponential one, provide the same results as the Gaussian model.\(^ {29} \)
FIG. 4. Electron mobility curves in β-SiC vs transverse effective field at room temperature: (a) only phonon scattering (solid line), (b) phonon and surface-roughness scattering (solid line), (c) Coulomb scattering due only to substrate doping impurities (solid circles), and (d) assuming, in addition, a typical interface charged layer of $N_i=1\times10^{11}$ cm$^{-2}$ (solid circles).

In our simulation the electron energy has been limited to 0.5 eV, since for higher electron energies the results obtained by the simulation are not likely to be very accurate, as a detailed bandstructure was not used. In accordance with the above, as the cubic silicon carbide bandgap is set to 2.36 eV (and therefore this sets the energy threshold for the impact ionization process), impact ionization has not been included in our simulation.

In order to incorporate the effect of Coulomb scattering in quantized inversion layers we have adopted a comprehensive Coulomb scattering model that includes the effects of the oxide-trapped and interface-trapped charge space correlation. This model thus takes into account the random nature of the charged centers in the Born approximation. Using this Coulomb scattering model we have been able to accurately reproduce experimental effective mobility in silicon inversion layers in a wide variety of situations.

Figure 4 shows simulated mobility curves at room temperature versus the transverse effective field ($E_{\text{EFF}}$ as defined by Sabnis et al.) at room temperature assuming (a) only phonon scattering (solid line), (b) phonon and surface-roughness scattering (solid squares), (c) Coulomb scattering due only to substrate doping impurities (triangles), and (d) assuming, in addition, a typical interface charged layer of $N_i=1\times10^{11}$ cm$^{-2}$ (solid circles). As can be seen in this figure, when only phonon scattering is taken into account, the electron mobility at low transverse electric fields approaches the bulk-mobility value ($10^5$ cm$^2$/Vs). The substrate doping concentration was assumed to be $N_A=1\times10^{16}$ cm$^{-3}$, and the parameters for the surface-roughness scattering were assumed to be $\Delta=1.4$ Å and $L=15$ Å. The contribution of each scattering mechanism as $E_{\text{EFF}}$ increases can be observed in the figure: At low transverse fields, the main scattering mechanism is Coulomb scattering. In contrast, at high transverse electric fields, the main mobility limitation is surface-roughness scattering. In the intermediate regime of electric fields, phonon scattering is the main cause of limitation of electron mobility. As a direct consequence of these limitations, β-SiC effective mobility curves show a bell shape, as in silicon, the result of a superposition of two opposing trends: the increase of Coulomb-limited mobility as the inversion charge increases, and the decrease of phonon and surface-roughness limited mobility as the transverse effective field increases.

IV. RESULTS AND DISCUSSION

To study the importance that the different scattering mechanisms have on the electron mobility in β-SiC inversion layers, we have made systematic simulations of electron mobility under different conditions of temperature, impurity concentrations, and taking into account the isolated contributions of the different scattering mechanisms. A comparison with electron mobility in silicon inversion layers has also been provided. In the following results, unless otherwise specified, the substrate doping concentration was assumed to be $N_A=1\times10^{16}$ cm$^{-3}$, and the parameters for the surface-roughness scattering were assumed to be $\Delta=1.4$ Å and $L=15$ Å.

A. Effect of temperature

The wide bandgap and the high Si–C bonding energy in silicon carbide makes this semiconductor appropriate for operation at very high temperatures. Figure 5 shows electron mobility curves for three different temperatures: $T=300$, 600, and 900 K. As can be seen, electron mobility falls significantly as the temperature increases. At the same time, the usual bell shape of mobility curves at lower temperatures is less pronounced as the temperature increases due to the increasing importance of the phonon-scattering contribution, which becomes the main scattering event. Apart from their very low values, mobility curves behave fairly well, even at such high temperatures.
B. Phonon scattering

We have already shown in Fig. 4 that phonon scattering limits mobility in the intermediate electric field region. We have simulated the phonon-limited mobility in SiC inversion layers, and have compared it to its counterpart in silicon inversion layers at room temperature. Figure 6 shows mobility curves at room temperature for both $\beta$-SiC and Si inversion layers taking into account only the effect of phonon scattering (both acoustic deformation potential scattering, polar-optical phonon interactions, and intervalley phonon events). For low transverse effective fields $E_{\text{EFF}}$ the two curves show the same trend. Nevertheless, the separation between the SiC and Si mobility curves increases in conjunction with the transverse effective field due to the contribution of polar-optical phonon scattering, which becomes the main phonon-scattering mechanism at high transverse electric fields. Electron mobility may also be somewhat influenced by SiO$_2$ polar-optical phonons in this high field region, but this contribution has been assumed to be small due to the small penetration of envelope functions in the oxide. At any rate, the contribution of phonons in this high electric field range is eventually masked by surface-roughness scattering.

It is important to note that the phonon-limited electron mobility at low transverse electric fields approaches the bulk-mobility value, since the electron gas spreads deeply into the bulk, and the quantization effects vanish.

C. Surface-roughness scattering

From the point of view of surface roughness the lower penetration of the inversion layer into the bulk (discussed in Sec. II) implies that such transport limitations could be worse in $\beta$-SiC than Si inversion layers. Figure 7 shows a mobility curve for $\beta$-SiC versus the transverse effective field taking into account only phonon and surface-roughness scattering (solid line). For the sake of comparison a Si mobility curve for the same conditions is also shown. It can be seen that the electron mobility is higher in Si than in SiC in the entire electric field range, even at high electric fields (where surface-roughness scattering dominates), and even though the surface-roughness parameters are the same for both the Si and SiC simulations. This can be explained, as mentioned before, due to the average penetration depth of the inversion layer in silicon carbide always being lower than that of silicon, which results in increased surface-roughness scattering in SiC.

Figure 8 shows the contribution of polar scattering to the electron mobility in $\beta$-SiC when only phonon and surface-roughness events are considered. It can be seen that at high effective fields, the contribution of polar scattering decreases due to a more important contribution of surface roughness.

![FIG. 6. Electron mobility curves in $\beta$-SiC (dashed line) and in Si (solid line) vs transverse effective field at room temperature taking into account only phonon scattering.](image)

![FIG. 7. Electron mobility curves in $\beta$-SiC (dashed line) and in Si (solid line) vs transverse effective field at room temperature taking into account only phonon scattering and surface-roughness scattering.](image)

![FIG. 8. (Dashed line) Electron mobility curves in $\beta$-SiC vs transverse effective field at room temperature taking into account only phonon scattering and surface-roughness scattering. (Solid line) Same as dashed line but without taking into account polar-phonon scattering.](image)
D. Coulomb scattering

As stated above, metal-oxide-semiconductor (MOS) devices fabricated on SiC are expected to be superior to those on silicon when operating under extreme conditions; high voltages, high frequencies, and high temperatures. In such conditions, the injection of mobile electrons inside the oxide is promoted, thus causing the degradation of the interface and the oxide. Moreover, these devices could be frequently exposed, in their potential application environments, to ionizing-radiation, which causes an increase in both interface-trapped and oxide-trapped charge densities. This fact significantly reduces that the screening of the electric fields grows.

To study the effect of Coulomb scattering we have calculated mobility curves in β-SiC (Fig. 9) for different interface-charge concentrations; (1) \(N_{it}=5\times10^9\ \text{cm}^{-2}\) (upper curve), (2) \(N_{it}=2.4\times10^{10}\ \text{cm}^{-2}\), (3) \(N_{it}=6\times10^{10}\ \text{cm}^{-2}\), (4) \(N_{it}=1.5\times10^{11}\ \text{cm}^{-2}\), (5) \(N_{it}=2.5\times10^{11}\ \text{cm}^{-2}\), (6) \(N_{it}=5\times10^{11}\ \text{cm}^{-2}\) (lower curve). We have assumed that all the charged centers are located right at the interface. Oxide charge densities as high as \(1\times10^{12}\ \text{cm}^{-2}\) have also been reported in the literature. However, the fact that the Coulomb interaction dependence is inversely proportional to the distance between the inversion charge and the oxide-trapped charge makes the contribution of the oxide charge to the total Coulomb scattering rate negligible in comparison to the Coulomb scattering rate produced by the high interface charge densities found in SiC devices. It is also apparent that all the curves are almost superposed at high electric fields, which again indicates that Coulomb scattering diminishes in importance with respect to the other mechanisms, mainly surface-roughness scattering and polar-optical scattering, as the electric fields grows.

β-SiC mobility curves have been compared in Fig. 10 to the silicon ones (dashed line) for different interface charge concentrations; (1) \(N_{it}=5\times10^9\ \text{cm}^{-2}\), (2) \(N_{it}=6\times10^{10}\ \text{cm}^{-2}\), (3) \(N_{it}=4\times10^{11}\ \text{cm}^{-2}\). As can be seen, the effect of the interface charge is more important in β-SiC than in Si inversion layers, since at low transverse electric fields, where Coulomb scattering is the main scattering event, mobility curves corresponding to Si are higher than β-SiC ones. To more clearly appreciate this fact, Fig. 11 shows the evolution of the mobility maximum in SiC (solid line) and in Si (dashed line) inversion layers versus the interface-trapped charge concentration. As expected, both curves decrease as the charge concentration increases. Nevertheless, this behavior is more acute in the case of silicon carbide devices, since the less the electrons spread into the semiconductor bulk, the more they are affected by interface-trapped charges, that is to say, the greater the Coulomb scattering rate. In addition, as shown in Fig. 2, the average penetration of electrons in the ground subband (subband 0), \(z_0\), is greater in β-SiC than in Si. This fact significantly reduces that the screening of

![FIG. 9. Electron mobility curves in β-SiC inversion layers vs transverse effective field at room temperature for different interface-trapped charge concentrations: (1) \(N_{it}=5\times10^9\ \text{cm}^{-2}\) (upper curve), (2) \(N_{it}=2.4\times10^{10}\ \text{cm}^{-2}\), (3) \(N_{it}=6\times10^{10}\ \text{cm}^{-2}\), (4) \(N_{it}=1.5\times10^{11}\ \text{cm}^{-2}\), (5) \(N_{it}=2.5\times10^{11}\ \text{cm}^{-2}\), (6) \(N_{it}=5\times10^{11}\ \text{cm}^{-2}\) (lower curve).](image)

![FIG. 10. Comparison of electron mobility curves in β-SiC inversion layers (solid line) and in silicon inversion layers (dashed line) for different interface-trapped charge concentrations: (1) \(N_{it}=5\times10^9\ \text{cm}^{-2}\), (2) \(N_{it}=6\times10^{10}\ \text{cm}^{-2}\), (3) \(N_{it}=4\times10^{11}\ \text{cm}^{-2}\).](image)

![FIG. 11. Evolution of mobility maximum in SiC (solid line) and in Si (dashed line) inversion layers vs the interface-trapped charge concentration.](image)
interface-charged centers, which plays a very important role in Coulomb scattering,\textsuperscript{17,20} thus increasing the Coulomb scattering rate and decreasing electron mobility.

Using the Matthiessen rule, we have isolated the Coulomb limited mobility for the same curves shown in Fig. 10, both for SiC (solid line) and Si (dashed line). The results are shown in Fig. 12. As a consequence of the greatest Coulomb scattering, the Coulomb limited mobility in $\beta$-SiC is lower than in Si. Nevertheless, as the effective field increases, the separation between the Coulomb limited mobility curves in $\beta$-SiC and in Si diminishes, since as shown in Fig. 1, the average distance of the inversion layer electrons to the interface in both cases tends to coincide. At the same time, the screening tends to be similar in both cases. Therefore, the same Coulomb limited mobility will be expected.

V. CONCLUSIONS

We have studied the transport properties of electrons in $\beta$-SiC quantized inversion layers. To do so, the Poisson and Schroedinger equations have been self-consistently solved in the MOS structure. A simple nonparabolic description of the $\beta$-SiC band structure has been considered. We have shown that, as a consequence of the effective mass values and for a fixed inversion charge concentration, $\beta$-SiC inversion layer electrons spread less into the bulk than Si ones. As a consequence, the defects of the SiO$_2$/$\beta$-SiC (interface roughness, Coulomb interaction with charged centers) will strongly affect electron transport properties.

Once the actual potential distribution, transverse effective field, and inversion and depletion charge concentrations in the structure have been calculated, the electron dynamics are simulated by the one electron Monte Carlo method. Phonon (acoustic deformation potential scattering, polar-optical phonon interactions, and intervalley phonon effects), surface-roughness and Coulomb scattering due to both bulk impurities and interface-trapped and oxide-trapped charges have been taken into account. We have presented simulated mobility curves for quantized $\beta$-SiC inversion layers taking into account the different scattering mechanisms, and have compared them to Si mobility curves. We have thus shown the importance of polar phonon scattering at high transverse effective fields, and the more important mobility limitation due to surface-roughness scattering.

Special interest has been paid to the effect of Coulomb scattering due to both interface- and oxide-trapped charges. We have simulated mobility curves for different interface-trapped charge concentrations, which have been compared with silicon mobility curves. We have seen that the effect of the interface-trapped and oxide-trapped charges are more acute in SiC than in Si. In summary, we have shown that electrons in silicon carbide inversion layers, at room and higher temperatures, are more affected by surface defects than they are in silicon inversion layers.

36 A. G. Sabnis and J. T. Clemens, IEDM Tech Dig. 79, 18 (1979).