Comprehensive Study of the Electron Scattering Mechanisms in 4H-SiC MOSFETs

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Abstract—The effects of doping concentration and temperature upon the transport properties in the channel of lateral n-channel SiC MOSFETs have been studied using current–voltage and Hall-effect measurements. To interpret the electrical measurements, numerical TCAD simulations have been performed. A simulation methodology that includes the calculation of the Hall factor in the channel of SiC MOSFETs has been developed and applied. In addition, a new model for the bulk mobility has been suggested to explain the temperature dependence of the MOSFET characteristics with different background doping concentrations. Based on the good agreement between the simulated and the measured results, scattering mechanisms in the channel of SiC MOSFETs have been studied.

Index Terms—Electron mobility, Hall effect, scattering mechanisms, SiC MOSFET.

I. INTRODUCTION

4H-SiC is a wide bandgap semiconductor that possesses a favorable combination of physical properties making it attractive for various applications in the electronic industry. Its wide bandgap, high thermal conductivity, high saturation velocity, and high electric breakdown field makes it the material of choice for power electronics. In addition, the ability to form SiO2 on SiC by thermal oxidation in a way similar to Si provides a good basis for the fabrication of SiC MOS-based electronic devices. However, despite the similarity of the oxides grown on Si and SiC, the oxidation process of SiC is different due to the presence of carbon and leads to a higher density of interface traps. For comparison, the density of interface traps at the Si/SiO2 interface in modern CMOS technology does not exceed \(10^{10} \text{ cm}^{-2}/\text{eV}\). In contrast, at the SiC/SiO2 interface, this value is about \(\sim 10^{11} \text{ cm}^{-2}/\text{eV}\) in the middle of the bandgap and \(10^{13} \text{ cm}^{-2}/\text{eV}\) or even more at the band edges of 4H-SiC [1], [2]. The quality of the interface between the semiconductor and the gate oxide is a critical factor for the device performance of MOSFETs with a surface channel. For example, the performance of lateral 4H-SiC MOSFETs is very low because of the low channel mobility. This is usually explained by the high density of interface traps that lead to strong Coulomb scattering at the interface charges and thus significantly reduce the channel mobility. For its improvement, the impact of Coulomb scattering at the charged interface traps has to be reduced. Currently, the main strategy for a reduction of the aforementioned scattering mechanism is based on methodologies for the passivation of the interface traps, e.g., by nitridation [3], [4]. However, in addition, the amount of charged interface traps, which affect the performance of MOSFETs, can be controlled by changing the background doping concentration \(N_A\) [5]–[7].

In this paper, the effects of doping concentration and temperature upon the transport properties in the channel of SiC MOSFETs have been studied. For this purpose, lateral 4H-SiC n-channel MOSFETs have been manufactured and electrically characterized by current–voltage as well as Hall-effect measurements. The main finding of this paper is that a change of the background doping concentration changes also the temperature dependence of the transport properties of SiC MOSFETs. To interpret the results of the measurements, numerical simulations have been performed with Sentaurus Device of Synopsys. For this, a simulation methodology has been developed and applied. Based on the good agreement between the simulations and the measurements, a comprehensive study of the scattering mechanisms in the channel with different doping concentrations and at different temperatures has been carried out. For a quantitative comparison between the contributions of the scattering mechanisms to the channel mobility of SiC MOSFETs, the dependence of the Hall mobility on the effective electric field has been calculated and is discussed.

II. TEST STRUCTURES

Lateral n-channel 4H-SiC MOSFETs have been fabricated on p-type 4°-off 4H-SiC (0001) Si-face substrates with...
aluminum concentrations \( N_A \) of \( 1 \times 10^{15}, 1 \times 10^{16}, 5 \times 10^{16}, \) and \( 5 \times 10^{17} \) cm\(^{-3}\). The channel length and width of the MOSFETs were 500 and 80 \( \mu \)m, respectively. To obtain the Al concentrations of \( 1 \times 10^{16} \) and \( 5 \times 10^{16} \) cm\(^{-3}\), box-shaped, p-type wells were fabricated by multiple Al-implantations into the epitaxial layer which had a background acceptor concentration of \( 1 \times 10^{15} \) cm\(^{-3}\). The gate oxide was grown by thermal oxidation in N\(_2\)O atmosphere at 1550 K and annealed at the same temperature for 30 min in an N\(_2\) ambient. The oxidation time for the MOSFET with the background doping concentration of \( 5 \times 10^{17} \) cm\(^{-3}\) was 180 min and lead to a thickness of the gate oxide of 34 nm. For the other MOSFETs, the oxidation time was 150 min that resulted in a gate oxide thickness of 25.5 nm.

To characterize the MOSFETs electrically, current–voltage and Hall-effect measurements were performed. The MOSFETs with the Al-doping concentrations of \( 1 \times 10^{16} \) and \( 5 \times 10^{16} \) cm\(^{-3}\) have been characterized at room temperature (300 K). The MOSFETs with the \( N_A \) values of \( 1 \times 10^{15} \) and \( 5 \times 10^{17} \) cm\(^{-3}\) have additionally been characterized in the temperature range from 150 to 500 K. The source–drain voltage \( V_D \) in the current–voltage and in the Hall-effect measurements was set to 0.1 V, and the gate voltage was varied between 0 and 20 V. The Hall-effect measurements were carried out using a permanent magnet with a magnetic field of 0.33 T. The choice of the low \( V_D \) allows to focus on the linear mode of operation of the SiC MOSFETs avoiding the problems of high-field electron transport. From the results of the Hall-effect measurements, the Hall mobility \( \mu_H \) and the drift-channel mobility \( \mu \) as well as the sheet carrier density of electrons \( n_{inv} \) in the inversion layer were determined as a function of gate voltage \( V_G \) from the measurable quantities considering the Hall factor \( r_H \) by the formulas

\[
\mu_H = \frac{V_H}{\rho I_D B} \tag{1}
\]

\[
\mu = \frac{\mu_H}{r_H} \tag{2}
\]

\[
n_{inv} = r_H \frac{I_D B}{q V_H} \tag{3}
\]

where \( I_D \) denotes the drain current, \( B \) is the magnetic field, \( q \) is the elementary charge, \( V_H \) is the Hall-effect voltage, and \( \rho \) is the channel resistivity.

To complement the Hall measurements for the evaluation of the interface trap density, capacitance–voltage measurements have been performed on a substrate oxidized in a similar way as the MOSFETs.

More details of the fabrication process as well as the measurement setup can be found elsewhere [7], [8].

### III. Experimental Results

It is widely accepted that the channel mobility in lateral MOSFETs, in particular in SiC MOSFETs, is determined by the following scattering mechanisms: Coulomb scattering at ionized impurities in the bulk and at the interface charges, surface-roughness scattering, as well as surface-phonon and bulk-phonon scattering [9], [10]. In Si MOSFETs, it was found that the electron channel mobility shows a universal behavior at high electric fields when plotted as a function of the effective electric field normal to the semiconductor surface. Processing and device conditions as well as doping concentrations do not affect the channel mobility in this regime significantly [11]. This result was taken as evidence that the channel mobility of Si MOSFETs is predominantly limited by the surface-phonon scattering.

For a first, qualitative assessment whether something similar can be found in SiC, the field dependence of the Hall mobility has been drawn in Fig. 1 for the available MOSFETs as a function of the effective normal electric field \( E_{eff} \). Following [11], \( E_{eff} \) has been calculated from:

\[
E_{eff} = \frac{q}{\varepsilon_S} \left( \frac{N_A x_d + \frac{1}{\eta} n_{inv}}{q^2 N_A} \right) \tag{4}
\]

with \( \varepsilon_S \) being the dielectric constant of the semiconductor and \( x_d \) is the depletion width given by

\[
x_d = \sqrt{\frac{4 \varepsilon_S k T n_i}{q^2 N_A}} \tag{5}
\]

where \( k \) is Boltzmann’s constant, \( T \) is the absolute temperature, and \( n_i \) is the intrinsic charge carrier concentration. For Fig. 1, a value of 2 was assumed for \( \eta \). In addition to the mobility curves, asymptotic trends of the mobility components associated with the surface-roughness scattering \( \mu_{SR} \sim E^{-2} \) and with the surface-phonon scattering \( \mu_{SP} \sim E^{-1/3} \) have been included for comparison.

In Fig. 1, it can be seen that the measured Hall mobility values of the inversion electrons in the channel do not lie on a common curve at high electric fields. At least for the studied range of electric fields, this allows us to conclude that it is not just surface-phonon scattering as in silicon that limits the high-field mobility in SiC. However, it is interesting to note that the Hall mobility of the lightest doped MOSFET reproduces the \( E^{-1/3} \) dependence for a wide range of electric fields. The same trend is observed to an increasingly smaller degree for higher doping concentrations. Going to lower effective field values, the Hall mobility decreases after a maximum. This indicates a change in the dominant scattering mechanism. The field dependence of the MOSFET with the highest doping concentration of \( 5 \times 10^{17} \) cm\(^{-3}\) apparently reflects only the
low-field branch. An increase of $\mu_H$ with the effective field as observed for low electric fields would be expected for a dominant Coulomb scattering at the interface charges.

To better identify the dominant scattering mechanism, the field dependence of the Hall mobility has been evaluated for the MOSFETs with the lowest and the highest $N_A$, i.e., $1 \times 10^{15}$ and $5 \times 10^{17}$ cm$^{-3}$, at different temperatures. Here, it should be noted that each kind of scattering mechanisms has its specific temperature dependence. As an example, with an increase in temperature, Coulomb scattering decreases, but phonon scattering increases. The effects on the respective mobility are vice versa. The dependence of the Hall mobility on the effective field is shown in Fig. 2 for the MOSFET with $N_A = 1 \times 10^{15}$ cm$^{-3}$ in the temperature range from 150 to 500 K.

While all curves in Fig. 2 follow approximately the $E^{-1/3}$ trend line associated with the surface-phonon scattering, it is interesting to note that the Hall mobility increases for all fields from 150 to 300 K, while it decreases again for higher temperatures. Similar results have been obtained in [12]. They showed that a suitable variation of process conditions led to a strong decrease of Coulomb scattering at the interface charges and consequently to a dominance of phonon scattering and an associated decrease of the field-effect mobility with temperature.

For the MOSFET with $N_A = 5 \times 10^{17}$ cm$^{-3}$, the dependence of the Hall mobility on the effective field is shown in Fig. 3 in the temperature range from 175 to 400 K. In contrast to the Hall mobility of the MOSFET with the lowest $N_A$, the Hall mobility for the MOSFET with the highest $N_A$ shows a continuous increase with increasing temperature from 175 to 400 K, following the asymptotic trend line $E_{\text{eff}}$. In particular, the temperature dependence of $\mu_H$ confirms the statement that Coulomb scattering at the interface charges dominates for the highly doped MOSFETs. This is also in agreement with the results in [13].

IV. SIMULATION RESULTS

The temperature dependence of the Hall mobility at the different doping concentrations can be better understood by analyzing the scattering mechanisms contributing to the channel mobility. In this paper, the available experimental data have been reproduced first using the numerical simulations with Sentaurus Device. Then, the electron mobility components associated with the main scattering mechanisms have been extracted from the numerical device simulation and analyzed. Because of convergence problems at low temperatures and the higher priority of elevated temperatures, the measurements below room temperature have not been further used in view of the limited project resources.

A. Simulation Model

Taking into account that low channel mobilities in lateral SiC MOSFETs are usually explained by Coulomb scattering at the interface charges, accurate models for the interface traps and the mobility degradation are of vital importance for the simulation. To obtain the energetic distribution of interface traps, an improved procedure was used [14]. At first, an approximate distribution of traps versus trap energy was extracted from the Hall-effect [15] and the complementary capacitance–voltage measurements. This was then used directly in Sentaurus Device via a table function and optimized to reproduce the three experimentally measured characteristics by the simulation: 1) $I_D(V_G)$; 2) $n_{\text{inv}}(V_G)$; and 3) $\mu(V_G)$. The mobility degradation model used in the simulations accounts for scattering mechanisms associated with Coulomb scattering at the ionized impurities in the bulk $\mu_{\text{IMP}}$ and at the interface charges $\mu_C$, surface-roughness $\mu_{\text{SR}}$, surface-phonon $\mu_{\text{SP}}$, and bulk-phonon scattering $\mu_{\text{BP}}$. The total channel mobility is assumed to result from Matthiessen’s rule as

$$\frac{1}{\mu} = \frac{1}{\mu_{\text{IMP}}} + \frac{1}{\mu_{\text{BP}}} + \frac{1}{\mu_C} + \frac{1}{\mu_{\text{SR}}} + \frac{1}{\mu_{\text{SP}}}.$$

(6)

Therein, the contributions from Coulomb scattering at ionized impurities $\mu_{\text{IMP}}$ and bulk-phonon scattering $\mu_{\text{BP}}$ are usually combined to the bulk mobility $\mu_B$

$$\frac{1}{\mu_B} = \frac{1}{\mu_{\text{IMP}}} + \frac{1}{\mu_{\text{BP}}}.$$

(7)

In this paper, to simulate the temperature dependence of the electrical characteristics of the studied MOSFETs with
low and high background doping concentrations, a new model for the bulk mobility component $\mu_B$ was developed on the basis of the conventional one [16, 17] and implemented into Sentaurus Device in the form

$$\mu_B = \mu_{\text{min}} \left( \frac{T}{300 \text{ K}} \right)^{\alpha} + \frac{\mu_{\text{BP}} - \mu_{\text{min}} \left( \frac{T}{300 \text{ K}} \right)^{\alpha}}{1 + \left( \frac{T}{300 \text{ K}} \right)^{\varphi} \left( \frac{N_A}{N_{\text{ref}}} \right)^{\nu}} \quad (8)$$

with the temperature dependence of the bulk-phonon related mobility $\mu_{\text{BP}}$ defined as a sum of two terms

$$\mu_{\text{BP}} = \mu_{\text{BP1}} \left( \frac{T}{300 \text{ K}} \right)^{\varphi} + \mu_{\text{BP2}} \left( \frac{T}{300 \text{ K}} \right)^{\nu}. \quad (9)$$

Therein, $\mu_{\text{min}}$ is the minimum value of the bulk mobility at high doping concentration at 300 K, $N_{\text{ref}}, \alpha, \varphi, z, \varphi$, and $\nu$ are fitting parameters. The values of the model parameters used in the simulations can be found in Table I.

The development of the new model (8) has been based on an analysis of scattering mechanisms in the channel of the SiC MOSFETs with the $N_A$ values of $1 \times 10^{15}$ and $5 \times 10^{17}$ cm$^{-3}$ with Sentaurus Device at different temperatures. It was found that the bulk-phonon scattering in SiC has to increase stronger with temperature than it was predicted by the conventional model developed originally for Si. This has been implemented by the description of the mobility component $\mu_{\text{BP}}$ via two terms, as shown in (9), instead of the conventional description where $\mu_{\text{BP}} \sim (T/300 \text{ K})^{-2.4}$ [16, 17]. More detailed discussions of the new model and its numeric implementation can be found in [14].

The reduction of the channel mobility due to Coulomb scattering at the interface charges was considered in the form as implemented in Sentaurus Device [18]

$$\mu_C = \frac{\mu_1 \left( \frac{T}{300 \text{ K}} \right)}{\left( \frac{N_C}{N_0} \right)^{\eta_2} D(x) f(E_\perp)} \quad (10)$$

where $\mu_1$ is a fitting parameter, $c$ is the concentration of the electrons near the interface, $N_C$ is the density of interface traps, $x$ is the distance from the interface, and $E_\perp$ is the electric field perpendicular to the oxide/semiconductor interface.

The functions $D(x)$ and $f(E_\perp)$ are given by

$$D(x) = e^{-x/[\epsilon_0]} \quad (11)$$

$$f(E_\perp) = 1 - e^{[-(E_\perp/E_0)^\gamma]} \quad (12)$$

The parameters $\mu_1$, $N_0$, $\eta_1$, $\eta_2$, $\gamma$, $I_{\text{crit}}$, $E_0$, and $\gamma$ were used with the default values of the model parameters taken from Si in Sentaurus Device. To reproduce the experimentally measured dependence of the mobility on the doping concentration, the model had to be calibrated for each $N_A$. For this purpose, the parameter $c_{\text{trans}}$ representing the screening of the carriers in the inversion layer was adjusted. By fitting the simulations to the measurements, the following values of $c_{\text{trans}}$ have been obtained: $2.8 \times 10^{16}$, $8 \times 10^{16}$, $2.5 \times 10^{17}$, and $1.55 \times 10^{18}$ cm$^{-3}$ for $N_A$ equal to $1 \times 10^{15}$, $1 \times 10^{16}$, $5 \times 10^{16}$, and $5 \times 10^{17}$ cm$^{-3}$, respectively.

The contribution attributed to the surface-roughness scattering was modeled in the form [18]

$$\mu_{\text{SR}} = \left[ \frac{(E_\perp/E_{\text{ref}})^2 + E_3^3}{\delta/\eta} \right]^{-1} \frac{1}{D} \quad (13)$$

where $E_{\text{ref}}$ is the reference electric field equal to 1 V/cm, while $\delta$ and $\eta$ are fitting parameters which depend on the roughness of the SiC/SiO$_2$ interface. The lower the roughness of the interface, the higher the values of $\delta$ and $\eta$.

Considering the dependence of $\mu_{\text{SR}}$ on the electric field $E_\perp$, the contribution of surface-roughness scattering is stronger at higher gate voltages. Taking this into account, the values of $\delta$ and $\eta$ were modified from the Si default values by bringing the simulated and the measured drain currents at higher $V_G$ into agreement. The values of $\delta$ and $\eta$ were found to be equal to $1.7 \times 10^{13}$ cm$^2$/V/s and $1.7 \times 10^{29}$ V$^2$/cm s for the MOSFET with $N_A = 5 \times 10^{17}$ cm$^{-3}$ and $t_{\text{ox}} = 34$ nm. For the three other MOSFETs with $t_{\text{ox}} = 25.5$ nm, $\delta$ and $\eta$ are equal to $1.6 \times 10^{14}$ cm$^2$/V/s and $1.6 \times 10^{30}$ V$^2$/cm s, respectively. It can be seen that the fitting parameters for the MOSFETs with different oxide thicknesses differ almost by a factor of 10, indicating that the MOSFET with the thicker oxide has a rougher interface than the thinner oxide. This result is in agreement with the work in [19], where it was shown that with increasing oxide thickness, the roughness of the interface increases.

Finally, the contribution attributed to the surface-roughness scattering was modeled in the form [18]

$$\mu_{\text{SP}} = \left[ \frac{B}{E_\perp} + \frac{C(N_A)^{a_1}}{E_\perp^{1/T}} \right] \frac{1}{D}. \quad (14)$$

The model parameters $B, C$, and $a_1$ in our simulations of 4H-SiC MOSFETs were taken from [20].

### B. Reproduction of the Current–Voltage Characteristics

Applying interface-trap and mobility-degradation models as described in Section IV-A, the current–voltage characteristics have numerically been simulated first at 300 K. A comparison of the simulations and measurements is shown in Fig. 4 for the four studied MOSFETs. As it can be seen, the models used in the simulations excellently reproduce the doping dependence of the measured drain current at room temperature. Changing
the temperature has two direct effects. First, all contributions of the scattering mechanisms to the channel mobility change according to their temperature dependence. Second, the bulk potential changes and with it the occupation of the interface traps. Both are considered accordingly in Sentaurus Device when the nominal device temperature is changed. A comparison of the simulations and measurements is shown in Figs. 5 and 6 for the MOSFETs with $N_A$ equal to $5 \times 10^{17}$ and $1 \times 10^{15}$ cm$^{-3}$, respectively.

As it can be seen, the models used in the simulation can also very well reproduce the temperature dependence of the current–voltage measurements for the MOSFETs with low and high $N_A$. From the comparison of the current–voltage characteristics in Figs. 5 and 6, it can be seen that the temperature dependence of the drain currents depends strongly on the background doping concentration. At high $N_A$, the drain current strongly increases in the studied temperature range with increasing temperature, while at low $N_A$, it is almost independent of temperature showing a slight increase at low gate voltages and a slight decrease at high gate voltages.

### C. Interpretation of Hall-Effect Measurements

The Hall-effect measurement is one of the straightforward methods to experimentally characterize the transport properties in the channel of the SiC MOSFETs. However, it is clear from (2) and (3) that the drift-channel mobility $\mu$ and the sheet carrier density $n_{inv}$ obtained are just as accurate as the Hall factor. Currently, it is common practice to assume $r_H$ being equal to unity [12]. However, in our previous works, it has been shown that the Hall factor in the channel of SiC MOSFETs differs significantly from unity and, moreover, depends on the gate voltage applied [21]. Thus, based on our recently developed method [22], the Hall factor in the studied SiC MOSFETs has been calculated at different doping concentrations and temperatures. The results of the calculation are shown in Figs. 7 and 8 for the MOSFETs with $N_A$ values of $5 \times 10^{16}$ and $1 \times 10^{16}$ cm$^{-3}$ for 300 K as well as with the $N_A$ values of $1 \times 10^{17}$ and $5 \times 10^{17}$ cm$^{-3}$ in the temperature range from 300 to 500 K and from 300 to 400 K, respectively.

In addition to the dependence of the Hall factor on the gate voltage, discussed in [21], the Hall factor depends on the doping concentration and temperature. With decreasing $N_A$, the Hall factor also decreases, which can mainly be related to a decrease of Coulomb scattering at the interface charges. A decrease of the Hall factor is also seen with increasing temperature. Taking the results in Figs. 7 and 8 and using (2) and (3), the results of the Hall-effect measurements have been corrected with the calculated Hall factor.
Fig. 8. Hall factor for the electron transport in the channel of SiC MOSFETs with $N_A = 5 \times 10^{17} \text{ cm}^{-3}$ at different temperatures.

Fig. 9. Comparison of the channel mobility from the simulations (lines) and the Hall-factor-corrected measurements (symbols) for the MOSFETs with different $N_A$ values at 300 K.

A comparison between the simulated and the measured sheet carrier density for different doping concentrations and temperatures has been published elsewhere [14], [23]. Here, we focus only on the channel mobility and the scattering mechanisms. A comparison of the channel mobility from the simulation and the Hall-factor-corrected measurements is shown in Fig. 9 for room temperature. The values of the simulated mobility were derived from the simulated current–voltage characteristics shown in Fig. 4 and the simulated sheet carrier density using

$$\mu = \frac{I_D L}{q W V D n_{inv}}$$

where $L$ and $W$ are the channel length and width, respectively.

The very good agreement in Fig. 9 between the simulated and the measured results for 300 K allows to apply this simulation methodology further to the temperature dependence of the transport properties in the channel of SiC MOSFETs. A comparison of the simulated and the Hall-factor-corrected channel mobility for the MOSFETs with the $N_A$ values of $5 \times 10^{17}$ and $1 \times 10^{15} \text{ cm}^{-3}$ at different temperatures is shown in Fig. 10.

For the lower $N_A$, it can be seen in Fig. 10(b) that the simulated channel mobilities reproduce the Hall-factor-corrected measurements very well for all temperatures.

For the higher $N_A$ in Fig. 10(a), the agreement is less perfect, but the trends are well reproduced. This indicates that there is further potential for the improvement of the mobility models used. Overall, the good agreement between the simulations and the measurements shown in Sections IV-B and IV-C confirms the self-consistency of the simulation methodology developed in this paper. Thus, the simulation results can be used further to study the effects of doping concentrations and temperatures upon the scattering mechanisms.

V. DISCUSSION

To analyze the scattering mechanisms in the channel of SiC MOSFETs and thus to understand the difference in the temperature dependence of the channel mobility, the mobility components have been calculated for different $N_A$ values and at different temperatures. This calculation has been performed using the method of small variations [14] based on the numerical simulation of the current–voltage characteristics which excellently reproduce the measured ones, as shown in Figs. 4–6. It should be noted that a splitting of the channel mobility into components allows to assess the relative contributions of the scattering mechanisms to the total mobility. The results of the extraction of the mobility components in the channel of SiC MOSFETs with the $N_A$ values of $5 \times 10^{17}$ and $1 \times 10^{15} \text{ cm}^{-3}$ at room temperature are shown in Figs. 11 and 12, respectively. For an easier comparison of the impact of all scattering mechanisms upon the total mobility, the inverse mobility is depicted.
In Fig. 11, it can be seen that the inverse mobility components associated with Coulomb scattering at ionized impurities in the bulk as well as with bulk-phonon and surface-phonon scattering are much lower than the inverse total mobility. This indicates their negligibility for the total channel mobility and, as a consequence, for the performance of SiC MOSFETs with high $N_A$. In contrast, the inverse mobility associated with Coulomb scattering at the interface charges and the surface-roughness scattering are the predominant scattering mechanisms.

For the SiC MOSFET with the lowest $N_A$, shown in Fig. 12, there are two main differences in the contributions of the scattering mechanisms to the channel mobility. The first one is that Coulomb scattering at the interface charges is on average by a factor of 10 lower than in the MOSFET with the highest $N_A$. The decrease of Coulomb scattering at the interface charges with decreasing doping concentration is reflected in an increase of the channel mobility, also shown in Fig. 9 for different $N_A$ values. A common explanation for this effect is that a decrease of $N_A$ leads to a decrease of the bulk potential and, as a consequence, of the occupation of the interface traps. Thus, the higher channel mobility at lower $N_A$ is often explained only by the lower amount of the charged interface traps. However, we found that an increase of the channel mobility with decreasing $N_A$ requires a broader view. One of the effects which have to be considered is the widening of the channel with decreasing $N_A$. Moving from the interface to the SiC bulk, the charged interface traps have less impact on the mobility due to the quick decrease of the Coulomb potential, which is screened by the inversion electrons. Thus, the mobility is expected to increase strongly when the channel gets wider. The second difference is that in the MOSFET with the lowest $N_A$ surface-phonon scattering contributes to the channel mobility much stronger than in the MOSFET with the highest $N_A$ and can be considered the second-most important scattering mechanism. This can be one of the explanations for the results shown in Fig. 1, where surface-phonon scattering describes well the trend of the Hall mobility with respect to the effective field.

In addition to the analysis performed at 300 K, the most relevant mobility components for the temperature dependence, i.e., $\mu_C$, $\mu_{SP}$, and $\mu_{BP}$, have been calculated at 400 K and compared in Fig. 13 with the calculations for 300 K.

In Fig. 13, it can be seen that $\mu_C$ increases strongly with increasing temperature which confirms the expected decrease of Coulomb scattering at the interface charges. This can mainly be explained by two interrelated effects. The first one is a decrease in the amount of charged traps due to the decrease of the bulk potential with temperature. The second one is an increase of the screening of the scattering centers due to the increase of the concentration of the inversion electrons. In contrast to Coulomb scattering, surface-phonon and bulk-phonon scattering increase with increasing temperature. Consequently, the respective mobility components decrease.

A comparison of the mobility components at different temperatures with their total mobilities explains the change of the temperature dependence of the channel mobility for the MOSFETs with high and low $N_A$ as follows. The mobility component $\mu_{SP}$ at high gate voltages has the same order of magnitude, as shown in Fig. 13, for both lightly and highly doped channels. Bulk-phonon scattering increases for both with increasing temperature. However, Coulomb scattering at the interface charges is at 300 K much stronger in the highly doped MOSFET than in the lowly doped one, as it was discussed above. In the MOSFETs with the high $N_A$, Coulomb scattering at the interface charges is so strong that the contributions of surface-phonon and bulk-phonon scattering are still negligible at 400 K. This means that for the temperature dependence of the SiC MOSFET with the high $N_A$, at least in the temperature range from 300 to 400 K, only Coulomb scattering plays a fundamental role. This leads to an increase of the channel mobility and, as a consequence, of the drain current with increasing temperature. In the case of the MOSFET with the low $N_A$, where Coulomb scattering is relatively low in comparison with the MOSFET with high $N_A$, an increase in temperature leads to the effect that the contributions of surface-phonon and bulk-phonon scattering become significant. Considering that the temperature dependence of bulk-phonon scattering is stronger than the temperature dependence of surface-phonon scattering, $\mu_{BP}$ decreases with increasing temperature faster and starts to dominate at high temperatures. This results in the reduction of the channel mobility with decreasing $N_A$.
To investigate the electron scattering mechanisms in lateral n-channel 4H-SiC MOSFETs with different channel doping concentrations, current–voltage and Hall-effect measurements have been performed as a function of temperature. To interpret the electrical measurements, a self-consistent TCAD simulation methodology has been developed which includes the calculation of the Hall factor in the channel, an improved method for the extraction of the interface trap density as a function of trap energy from the measurements, and a new bulk-mobility model. Based on the good agreement between the simulations and the measurements, explanations for the effects of doping and temperature upon the scattering mechanisms and further on the temperature dependence of the drain current have been obtained.

VI. CONCLUSION

To investigate the electron scattering mechanisms in lateral n-channel 4H-SiC MOSFETs with different channel doping concentrations, current–voltage and Hall-effect measurements have been performed as a function of temperature. To interpret the electrical measurements, a self-consistent TCAD simulation methodology has been developed which includes the calculation of the Hall factor in the channel, an improved method for the extraction of the interface trap density as a function of trap energy from the measurements, and a new bulk-mobility model. Based on the good agreement between the simulations and the measurements, explanations for the effects of doping and temperature upon the scattering mechanisms and further on the temperature dependence of the drain current have been obtained.

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