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Impact of acceptor concentration on electrical properties and density of interface states of 4H-SiC n-metal-oxide-semiconductor field effect transistors studied by Hall effect

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Silicon carbide n-type metal-oxide-semiconductor field effect transistors (MOSFETs) with different p-body acceptor concentrations were characterized by Hall effect. Normally OFF MOSFETs with good transfer characteristics and low threshold voltage were obtained with a peak mobility of $\sim$145 cm^2 V^{-1} s^{-1} for the lowest acceptor concentration. The results are explained in terms of an increase of Coulomb scattering centers when increasing the background doping. These scattering centers are associated to fixed oxide and trapped interface charges. Additionally, the observed mobility improvement is not related to a decrease of the interface states density as a function of background doping. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4908123]

The 4H polytype of silicon carbide (SiC) is a wide bandgap semiconductor with superior properties that is foreseen to replace silicon in power and high-temperature applications. In recent years, due to the maturity in material processing and device technology, SiC Metal-Oxide-Semiconductor Field Effect Transistors (MOSFET) have become commercially available. However, the low inversion-layer electron mobility in 4H-SiC MOSFETs remains a major limiting problem for applications. This poor mobility is generally assumed to be related to very high densities of interface states (D_{it}). Thus, numerous papers have focused on the role of D_{it} on electrical properties of Si-face 4H-SiC MOSFETs.[1,2]

It has been shown that H_2 annealing reduces D_{it} but the improvement in channel mobility is small.[3–5] Chung *et al.*[6] demonstrated that the field-effect mobility of Si-face 4H-SiC MOSFETs can be increased to 30–35 cm^2/V s by NO annealing. The nitridation techniques (NO, N_2O, N^+ implantation) have also been intensively investigated to reduce the D_{it}, leading to a mobility improvement up to 80 cm^{-2}/V s for a MOSFET with 5×10^{15} cm^{-3} p-body acceptor concentration. In addition, it has been shown that in n-type MOS capacitors, D_{it} near the conduction band edge E_C is reduced by nitrogen implantation.[7–9] In fact, nitrogen treatments are not the only processes that have an influence on electrical properties. For instance, Kimoto *et al.*[10] reported on the increase of the mobility with decreasing the doping concentration of the p-body for various crystal faces. However, while proposing an explanation for this effect in terms of a reduced surface roughness scattering at low doping concentration, the impact of p-body doping concentration on D_{it} was not investigated. Clearly, it is necessary to better understand the influence of the different fabrication processes on SiC devices in order to further improve their electrical properties.

Within this context, the aim of this paper is to study the impact of the p-body acceptor concentration (N_A) on electrical properties of SiC n-channel MOSFETs, with an oxide grown under N_2O atmosphere, and their relationship with D_{it}. Electrical properties have been determined by the Hall effect technique. Compared to other techniques employed to determine the mobility (effective and field effect mobilities), Hall effect measurements allow the determination of Hall mobility and inversion carrier density independently of threshold voltage, which is difficult to accurately determine in the case of MOSFETs with high D_{it}.[11] Moreover, the Hall effect allows the determination of D_{it}, as demonstrated by Saks,[11] without needing to use n-type MOS capacitors, as for the C(V) technique.

Hall-bar n-channel MOSFETs (with a channel length of 500 μm and a channel width of 80 μm) were fabricated on 4° off-axis (0001) Si-face 4H-SiC epitaxial layers (from CREE Inc.) at the Fraunhofer Institute for Integrated Systems and Device Technology. Aluminum concentrations from 1×10^{15} to 3.5×10^{17} cm^{-3} of the p-body region were achieved using two methods: (i) Aluminum (Al) doping during the epitaxial layer growth (epitaxial MOSFET) or (ii) p-well fabrication by multiple Al implants (implanted MOSFET) at 300 K on n-type epitaxial layers. The gate oxide, of about 26 nm, was grown by thermal oxidation in N_2O atmosphere at 1553 K, followed by annealing in nitrogen for 30 min at the same temperature. Table I summarizes p-body doping concentrations and doping method of the fabricated MOSFETs. The detailed fabrication process is described elsewhere.[12]

Hall measurements were performed using a modified Accent HL 5500PC Hall effect system. All measurements were carried out at 300 K with a source-drain voltage of 100 mV and gate voltages (V_G) up to 20 V. A detailed description of the

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TABLE I. Main characteristics of SiC MOSFETs: p-body acceptor concentration.

Al concentration (cm^{-3}): N_A	3.5×10^{17}	1×10^{17}	5×10^{16}	1×10^{16}	5×10^{15}	1×10^{15}
Substrate	p-well	p-well	p-well	p-well	p-well	Epitaxial

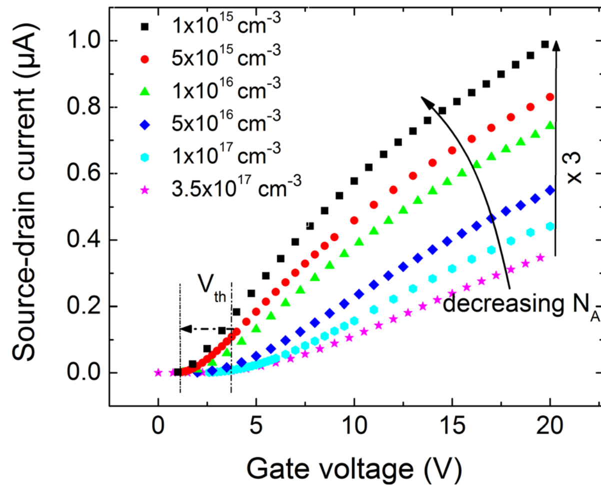

FIG. 1. Drain current as a function of gate voltage for MOSFETs with different acceptors concentrations.

experimental setup can be found in Ref. 13. Concerning the Hall scattering factor r_H, recent theoretical investigations[14] have proposed that r_H can be higher than unity; however, reliable experimental measurements of this parameter are still missing. In this work, r_H was therefore considered equal to 1 for all the investigated samples. This choice is not expected to affect the interpretation of the results.

Figure 1 shows the transfer characteristics (I_D-V_G) obtained for different values of N_A at 300 K. A significant improvement of the transistor output current (more than 3 times) and a decrease of V_{th} are observed when decreasing N_A. The arrows in Figure 1 indicate the direction of the changes for decreasing N_A. For all MOSFETs, the V_{th} values remain positive, i.e., all devices are normally OFF, which is an important aspect for application purposes. However, for N_A values below 5×10^{16} cm^{-3}, such normally OFF MOSFETs cannot theoretically be achieved,[15] unless a large amount of negative charges is present between the gate and the inversion channel region, such as those resulting from carriers trapped by interface states.

Figures 2(a) and 2(b) show, respectively, the Hall mobility μ_H and the inversion carrier density n_{inv} as a function of V_G for devices with different N_A measured at 300 K. Similar to the output current, we observe a strong improvement of channel mobility when decreasing N_A. This behavior has been also observed in Si (Ref. 16) and in 4H-SiC (Ref. 17) MOSFETs. The maximum peak mobility value is of $\sim$145 cm^2 V^{-1} s^{-1} for the MOSFET with lowest N_A. It is worth noting that this mobility value is among the highest ever achieved, showing the efficiency of the fabrication process.[13] For comparison, we can cite Okamoto *et al.*[18] who obtained a peak mobility of 89 cm^2 V^{-1} s^{-1} by introducing phosphorous atoms at the SiO_2/SiC interface or Sveinbjörnsson *et al.*[19] who achieved a mobility of 150 cm^2 V^{-1} s^{-1} by using alkali atoms leading to contaminated and unreliable oxides. Furthermore, the mobility behavior changes with N_A. For devices with low N_A, μ_H increases with V_G and then decreases while for devices with high N_A, μ_H shows a slight increase and then saturates.

Comparing the behavior of μ_H to that of n_{inv}, we observe a large increase of μ_H with decreasing p-body doping concentration while the effect on n_{inv} is rather limited. Indeed, only a slight difference in slope of $n_{inv}(V_G)$ curves can be observed for voltages higher than 12 V, clearly indicating that the inversion carrier density is not correlated to the observed mobility behavior.

Alternatively, considering that Coulomb scattering by interface charges is the dominant mechansim[20] in the channel of SiC MOSFETs, the mobility degradation observed when increasing the p-body doping concentration might be due to the increase of interface charges. These Coulomb scattering centers can be associated with interface trapped charges, n_{it}, related to the interface state density, D_{it}, or have their origin in fixed charges located near the interface, such as fixed oxide charges, n_{ox}. Both types of charges will be calculated and discussed in the following.

In this respect, we first investigated the density of interface states. Using the method detailed in Ref. 21, D_{it} can be obtained from the comparison of the slopes of theoretical and experimental $n_{inv}(V_G)$ curves. Theoretical curves stands for calculated curves without taking account of D_{it} and were obtained using Eq. (1), where Q_{sc} is the charge in the space charge region (calculated here by solving Poisson equation using Fermi-Dirac statistics[22]), C_{ox} is the oxide capacitance

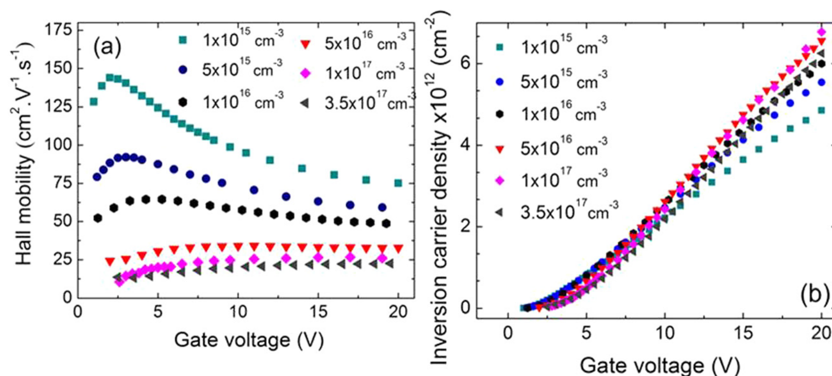

FIG. 2. (a) Hall mobility and (b) inversion carrier density as a function of gate voltage for MOSFETs with different p-body acceptors concentrations at 300 K.

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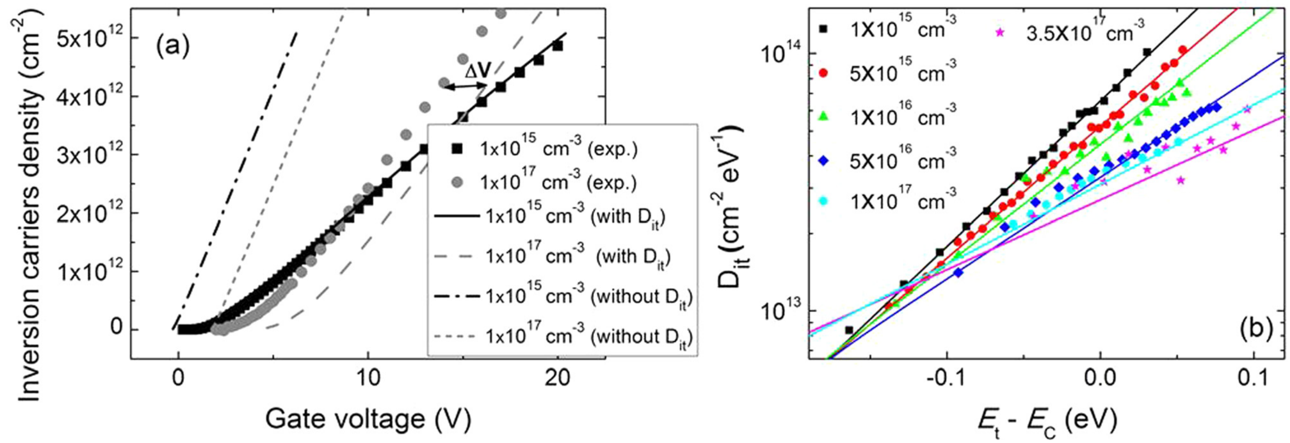

FIG. 3. (a) Experimental (symbols), theoretical ("without D_{it}"), and calculated ("with D_{it}") inversion carriers density as a function gate voltage for devices with N_A of 10^{15} and $10^{17}\,cm^{-3}$, and curves (b) density of interface states as a function of trap energy for N_A values as specified in the figure.

per unit area determined by classical C(V) measurements, n_{it} is the density of trapped charges (for theoretical curves: $n_{it}=0$), ψ_s is the surface potential and ϕ_{ms} the difference between the work functions of the gate metal and the semiconductor. An example is shown in Figure 3(a) for two p-body doping concentrations ($10^{15}\,cm^{-3}$ and $10^{17}\,cm^{-3}$). The difference between the slopes of theoretical ("without D_{it}") and experimental (symbols) $n_{inv}(V_G)$ curves indicates that high levels of D_{it} are present in these structures

$$V_G(\psi s) = \frac{Q_{SC}(\psi s)}{C_{ox}} + \frac{q\,n_{it}(\psi s)}{C_{ox}} + \psi s + \phi_{ms}. \quad (1)$$

D_{it} values for all samples investigated in this work are reported in Figure 3(b) (symbols). D_{it} extends from the near conduction band edge to a few 100 meV into the conduction band and reaches very high trap concentration levels ($\sim 10^{14}\,cm^{-2}\,eV^{-1}$). D_{it} curves were fitted (solid lines in Fig. 3(b)) using

$$D_{it} = \Delta \exp\left(\frac{E_t - E_c}{\sigma}\right), \quad (2)$$

where Δ is the band-edge density of states, σ is band-tail energy, E_t is trap energy, and E_c is conduction band energy. Calculated values of Δ and σ for different MOSFETs are reported in Table II. One can notice, from the values of Δ but also directly from Figure 3(b) that, for $E_t - E_c > -0.1$ eV, devices with low N_A show higher D_{it} than MOSFETs with high N_A. This important result implies that, in the voltage range of this study, the global increase of mobility observed, when N_A is decreased, is not related to a decrease of D_{it}. Significant μ_H improvements in concomitance with small variations in D_{it} were also reported when the impact of other experimental parameters, such as the annealing ambient,[24] were investigated.

Knowing D_{it}, it is now possible to determine the density of fixed oxide charges, n_{ox}, located near the SiC/SiO_2 interface. To this purpose, the $n_{inv}(V_G)$ curves were calculated taking into account D_{it}. These calculations were done using Eq. (1), with n_{it} obtained by integrating Eq. (2) (with Δ and σ values of Table II), from intrinsic level E_i to Fermi level E_F.

Figure 3(a) reports the result of this calculation ("with D_{it}" curves) for two doping levels ($10^{15}\,cm^{-3}$ and $10^{17}\,cm^{-3}$). We observe that the simulated curves exhibit the same slope dependence as the experimental ones (symbols), proving that high levels of D_{it}, calculated in all devices, are responsible for the large differences between experimental and theoretical $n_{inv}(V_G)$ behaviors.

Moreover, a systematic voltage offset ΔV was found for all devices: from 0.4 V for device with $N_A = 10^5\,cm^{-3}$, up to 6.6 V for device with $N_A = 3.5 \times 10^5\,cm^{-3}$. This voltage can be taken into account by simply adding a supplementary constant term (independent of gate voltage) in Eq. (1). In all cases, the simulated $n_{inv}(V_G)$ curves are shifted towards higher voltages with respect to the experimental ones (cf. Figure 3(a) for a background doping of $10^{17}\,cm^{-3}$), while the offset increases with increasing N_A. The direction of the shift indicates that fixed charges should be positive, and thus, are most probably oxide fixed charges, n_{ox}. For all the devices, n_{ox} was therefore determined from the voltage offset using the following equation: $\Delta V = q\,n_{ox}/C_{ox}$. Results are shown in Fig. 4 (black squares). It clearly appears that n_{ox} increases with increasing background doping N_A. The origin of charges resulting in an increase of n_{ox} is not yet well understood but it can be related to oxidation process in N_2O atmosphere. Nevertheless, the increase of n_{ox} with increasing N_A can be related to an increase of Coulomb scattering centers and therefore explain the degradation of mobility with increasing N_A shown in Figure 2(a).

Finally, on the basis of the D_{it} calculations presented above, the density of charges trapped by interface states, n_{it}, can be estimated. Indeed, assuming that the parameters used

TABLE II. Calculated values of Δ and σ parameters of interface traps density fits.

Al concentration (cm^{-3})	3.5×10^{17}	1×10^{17}	5×10^{16}	1×10^{16}	5×10^{15}	1×10^{15}
Δ ($cm^{-2}\,eV^{-1}$) $\times 10^{13}$	2.7	3.1	3.3	4.3	4.9	6.3
σ (eV)	0.16	0.14	0.11	0.095	0.09	0.08

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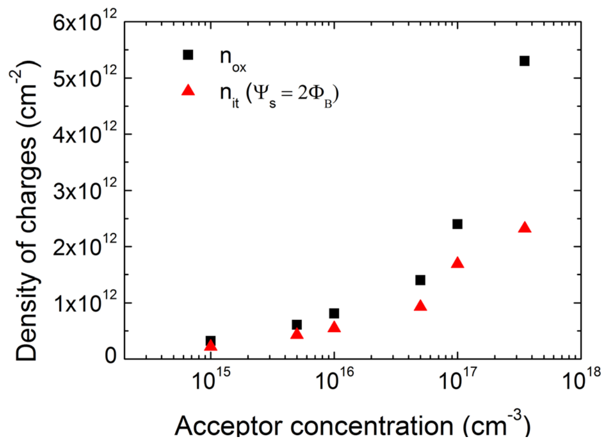

FIG. 4. Density of fixed oxide charges (n_{ox}) and density of interface trapped charges related to D_{it} (n_{it}) as a function of the p-body acceptor concentration.

to fit the calculated D_{it} values (cf. Table II and Figure 3(b)) are still valid at energies lower than those used for their determination, it is possible to estimate the value of n_{it} at the onset of strong inversion (i.e., $\psi_S = 2\ \phi_B$) using the following equation:[21]

$$n_{it}(\psi_S = 2\phi_B) = \int_{E_i}^{E_i+q(2\phi_B)} D_{it} dE, \qquad (3)$$

where ψ_S and ϕ_B are the surface and bulk potential, respectively, E_i is the intrinsic energy level and Eq. (2) was used for D_{it} with Δ and σ values of Table II.

The calculated n_{it} values are presented in Figure 4 (red triangles). Similar to the fixed oxide charges n_{ox}, it can be noted that n_{it} also increases with increasing N_A. Indeed, with increasing N_A, the band bending at the onset of strong inversion increases. As a consequence, the energetic distance between the Fermi level and the conduction band edge at the SiC/SiO_2-interface decreases. Hence, an increasing number of interface states will be energetically located below the Fermi level. Thereby, interface traps below the Fermi level effectively trap electrons and thus contribute to an increase of the interface trapped charge density n_{it} with increasing N_A.[23]

The results presented in this study clearly show that the mobility degradation observed when increasing the background doping is not directly related to an increase of D_{it} (which exhibits a weak dependence on doping) but rather to an increase of Coulomb scattering centers associated to interface charges. This implies that when the highest mobility values are measured (i.e., for low background doping and at low V_G values), other scattering mechanisms (such as phonon or surface scattering) might control the carrier transport behavior, contributing for instance to the appearance of the mobility peaks observed below 5 V for doping levels lower than $10^{16}\,cm^{-3}$. Further experiments, involving field and temperature dependent mobility measurements, supported by theoretical simulations, should be able to clarify this issue.

In summary, a systematic study was carried out by Hall effect on transport properties in the n-channel of silicon carbide MOSFETs with different p-body acceptor concentrations. Normally OFF MOSFETs with better transfer characteristic, low threshold voltage, and high carrier mobility have been obtained at low p-body acceptor concentration. Peak Hall mobility varies from ~20 to ~145 $cm^2\ V^{-1}\ s^{-1}$ as the p-body acceptor concentration varies from 3.5×10^{17} to $10^{15}\,cm^{-3}$. The mobility improvement observed when N_A is decreased is not correlated to a decrease of density of interface traps in itself. In contrast, Coulomb scattering centers associated with fixed oxide charges as well as interface trapped charges are found to increase when increasing the background doping, thus explaining the mobility degradation when N_A is increased.

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