Hall effect characterization of 4H-SiC MOSFETs: Influence of nitrogen channel implantation

V. Mortet\textsuperscript{1,2a}, E. Bedel-Pereira\textsuperscript{1,2,b}, J.F. Bobo\textsuperscript{3,c}, F. Cristiano\textsuperscript{1,2,d}, C. Strenger\textsuperscript{4,5,e} V. Uhnevionak\textsuperscript{5,f}, A. Burenkov\textsuperscript{5,g} and A.J. Bauer\textsuperscript{5,h}

\textsuperscript{1}CNRS, LAAS, 7 avenue du colonel Roche, 31400 Toulouse, France
\textsuperscript{2}Univ de Toulouse, LAAS, 31400 Toulouse, France
\textsuperscript{3}CNRS, CEMES, 29 rue Jeanne Marvig, 31400 Toulouse, France.
\textsuperscript{4}Department of Electron Devices, Cauerstrasse 6, 91058 Erlangen, Germany.
\textsuperscript{5}Fraunhofer IISB, Schottkystrasse 10, 91058 Erlangen, Germany.
\textsuperscript{a}vmortet@laas.fr, \textsuperscript{b}elena@laas.fr, \textsuperscript{c}jfbobo@cemes.fr, \textsuperscript{d}cfuccio@laas.fr, \textsuperscript{e}christian.strenger@leb.eei.uni-erlangen.de, \textsuperscript{f}viktoryia.uhnevionak@iisb.fraunhofer.de, \textsuperscript{g}alex.Burenkov@iisb.fraunhofer.de, \textsuperscript{h}anton.bauer@iisb.fraunhofer.de.

Keywords: 4H-SiC, MOSFET, Hall effect, Hall mobility, charge carrier density, Coulomb scattering, nitrogen implantation

Abstract. Effect of a shallow nitrogen implantation in the channel region of n-channel 4H-SiC Hall bar MOSFETs on their electrical properties has been characterized by Hall effect. A significant improvement of Hall mobility in normally-off devices is observed with increasing nitrogen implantation dose up to $10^{13}$ cm\textsuperscript{-2} with a peak Hall mobility of 42.4 cm\textsuperscript{2}.V\textsuperscript{-1}.s\textsuperscript{-1}. Coulomb scattering as dominant scattering mechanism up to room temperature is demonstrated using temperature dependent MOS-Hall effect characterization.

Introduction

Today, silicon carbide (SiC) is certainly the most promising semiconductor for future high-temperature and high-power electronic devices due to its superior physical and electrical properties compared to silicon. However, the potential of SiC is limited by several problems [1, 2]; one blocking point for the development of metal oxide semiconductor field effect transistors (MOSFETs) is the large density of traps at the SiC/SiO\textsubscript{2} interface. These traps can capture charges and act as Coulumbic scattering centers and hence reduce the mobility of channel electrons. Because of the large density of interface traps, commonly used transfer characteristic analyses are not suitable for the determination of electrical transport properties [3, 4]. Several reports have recently shown the beneficial effect of nitrogen (N) implantation in SiC MOSFETs [5-7]. In this paper, we report the electrical transport properties measured by Hall effect of 4H-SiC n-channel Hall bar MOSFETs fabricated with different N implantation doses ($N_{\text{impl}}$) below the gate area. The measurements have been performed in a wide temperature range to infer the dominant scattering mechanisms.

Experimental

Samples. MOSFETs were fabricated on p-implanted wells (with an aluminum concentration of 5·$10^{17}$ at.cm\textsuperscript{-3}) in n-type 4°-off angle 4H-SiC (0001) epilayers from CREE Inc with a net donor concentration of 8·$10^{15}$ at.cm\textsuperscript{-3}. Prior to implantation annealing and oxidation in N\textsubscript{2}O atmosphere, nitrogen was implanted in the channel region with different doses with an energy of 20 keV (see table 1). A detailed description of the fabrication process can be found in [8]. A schematic cross section of MOSFETs is shown in Fig. 1. The channel length (L) and width (W) of the Hall-bar MOSFETs used in this study are 500 µm and 80 µm respectively. The distance between the voltage...
taps for Hall measurements is 100 µm. Electrical characteristics of N implanted MOSFETs are compared to not channel implanted one fabricated on a p-type epitaxial SiC layer with the same nominal characteristics without N implantation [9].

**MOS Hall effect setup.** Electrical properties of MOSFETs were measured in a wide temperature range (50 – 500 K) and for gate voltages up to 20 V. MOS Hall effect measurements are carried out using an HL 5500PC Hall effect measurement system equipped with a cryostat (90 – 500 K) from ACCENT™ with a permanent magnet (0.33 T) and a Physical Properties Measurement System (4 – 400 K) from Quantum Design with a variable magnetic field (0-9 T). A scheme of the MOS Hall effect setup is represented in Fig. 2. Measurements using the HL 5500PC are automated using a homemade LabView program. A particular attention to voltage sources and meters selection, cabling and electromagnetic shielding has been paid due the low level of the Hall voltage (~ 10 µV at 0.33 T) and the drain current (I_{DS} < 1 µA). Noise level has been minimized using a battery for drain bias (V_{DS} = 100 mV) and the Hall voltage was measured using a Keithley 2182A will internal low band pass filter with a cut off frequency f_c = 18 Hz. A Keithley 2612A is used to bias the gate and to measure the drain current. For reliable measurements the MOSFET must be in the linear operating region, i.e. V_{th} << V_{GS} and V_{DS} < V_{GS} - V_{th}, with V_{GS}, V_{DS} and V_{th} the gate-source, drain-source and the threshold voltages respectively. The mobility (µ_{Hall}) and the charge carrier density (n_{inv}) were calculated assuming a Hall scattering factor r_H = 1.

Results and discussion

Transfer characteristics of different MOSFETs are presented in Fig. 3. An increase in the source-drain current (I_{DS}) is observed with increasing N_{impl}. Despite the different MOSFET fabrication processes compared to Poggi et al. [10], this result also shows the benefit of N implantation on MOSFETs’ electrical characteristic. In contrary to their results, a change in MOSFETs’ operation mode from enhancement to depletion with negative V_{th} is observed at high nitrogen implantation doses (i.e. N_{impl} ≥ 5×10^{13} at.cm^{-2}). This difference can be explained by an incomplete N activation due to different annealing conditions employed in [10]. The switch to depletion mode at high N_{impl} is attributed to the counter doping of the p-type well [11-12]. Our results together with those of Poggi et al. [10] and Dhar et al. [12] show that the optimal N_{impl} is a function of bulk acceptor concentration and annealing process.
The free electron density in the inversion layer \( n_{\text{inv}} \) increases linearly with \( V_{\text{GS}} \) whereby \( \partial n_{\text{inv}}/\partial V_{\text{G}} \sim 4 \times 10^{11} \text{cm}^{-2} \text{V}^{-1} \) is by a factor of two lower compared to the ideal (e.g. interface trap free) case \( C_{\text{ox}}/q \sim 8.1 \times 10^{11} \text{cm}^{-2} \). This discrepancy is due to electron trapping at the SiC/SiO\(_2\) interface [4]. Measured \( \mu_{\text{Hall}} \) of the enhancement MOSFETs is reported in Fig. 4. as a function of the \( V_{\text{GS}} \). The rise of carrier mobility with \( N_{\text{impl}} \) explains the better transfer characteristics of implanted enhancement MOSFETs. \( \mu_{\text{Hall}} \) behavior changes with the implantation doses: while \( \mu_{\text{Hall}} \) of MOSFETs N0 and p-epi only rise slightly, \( \mu_{\text{Hall}} \) of N implanted MOSFETs rises, passes a maximum and decreases. This behavior is more pronounced on MOSFET N2, (i.e \( N_{\text{impl}} = 10^{13} \text{at/cm}^2 \) ) where mobility peaks to a value of 42.4 \( \text{cm}^2 \text{V}^{-1} \text{s}^{-1} \). It is acknowledged that \( \mu_{\text{Hall}} \) in the inversion layer is limited by different scattering mechanisms: Coulomb scattering, phonon scattering and surface roughness scattering, [13] that depend on both effective field \( (E_{\text{eff}}) \) and temperature. At large gate voltages, \( E_{\text{eff}} \) is proportional to \( V_{\text{GS}} \) as the charge in the inversion layer is large compared to the charge in the depletion layer. However, dependence of \( \mu_{\text{Hall}} \) on \( V_{\text{GS}} \) at room temperature does not allow clear determination of a dominant scattering mechanism, thus additional temperature-dependent Hall measurements have been carried out. \( \mu_{\text{Hall}} \) vs \( V_{\text{GS}} \) of MOSFET N0 is shown on Fig. 5 for different temperatures. It rises and seems to saturate with increasing \( V_{\text{GS}} \) at a temperature higher than \( \sim 150 \text{K} \) while it appears linear at lower temperatures. A linear increase of \( \mu_{\text{Hall}} \) with \( V_{\text{GS}} \) or \( E_{\text{eff}} \) is a signature of Coulomb scattering. This is further confirmed from Fig. 6 that shows Hall mobility’s linearity with temperature for constant \( n_{\text{inv}} \) (i.e. constant \( E_{\text{eff}} \) ) up to room temperature for MOSFET N2 and above for N0 as well as for p-epi MOSFETs. This result is
consistent with Ref. [14]. Apparent saturation above room temperature of MOSFET N2’s $\mu_{\text{Hall}}$ indicates a different dominant scattering that cannot completely accessed until further high temperature (> 500 K) characterizations [15]. In addition, an increase in $\partial n_{\text{inv}}/\partial V_{\text{GS}}$ and a large increase of $V_{\text{th}}$ are observed at low temperature. These behaviors are believed to arise from electron trapping at the SiC/SiO$_2$ interface and shall be further investigated.

Summary
Electrical properties of n-channel 4H-SiC MOSFETs implanted with different N doses in the channel region have been characterized by MOS-Hall effect measurements. A significant improvement of Hall mobility is observed with increasing nitrogen implantation dose to $10^{13}$ cm$^{-2}$ before the change of MOSFET’s operation mode from enhancement to depletion due to nitrogen counter doping. Coulomb scattering as dominant scattering mechanism up to room temperature is demonstrated using temperature dependent measurements.

Acknowledgments
This work has been performed by the French-German Consortium MobiSiC and supported by the Inter Carnot Fraunhofer Program (PICF) from BMBF (Grant 01SF0804) and ANR.

References