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Ni/Heavily-Doped 4H-SiC Schottky Contacts

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Abstract. In this work, we focus on the electrical characterization of Ni Schottky contact on n-type heavily doped (N_D>10^{19} cm^{-3}) 4H-SiC layer, achieved by P-ion implantation. In particular, the forward current–voltage characterization of Schottky diodes showed a reduced turn-on voltage for the Ni/heavily-doped 4H-SiC if compared to a reference Ni/4H-SiC Schottky contact fabricated under similar conditions but without implant. Moreover, it was observed the predominance of a thermionic-field-emission (TFE) mechanism for the current transport through the interface. From a current-voltage-temperature (I-V-T) study, the temperature-dependence of the Schottky barrier and doping concentration were evaluated, obtaining a reduction of the barrier (from 1.77 to 1.66 eV), while the doping concentration maintains constant around 1.96×10^{19} cm^{-3}. This study provides useful insights for a deeper comprehension of the electrical behavior of Ni contacts and can have possible applications in 4H-SiC Schottky diode technology.

Introduction

Nowadays, 4H-SiC-based devices such as Schottky barrier diodes (SBDs) and metal–oxide–semiconductor field effect transistors (MOSFETs), have reached a high technological maturity and performances (low on-state voltage drop, high switching speed, high breakdown voltage, high temperature operation, etc.), and they can be largely employed in several applications [1]. In spite of the huge progresses, there are still margins of performance improvement associated to the optimization of the metal/semiconductor contact characteristics. Generally, the Schottky barrier properties are driven by an appropriate choice of metal (e.g., low work-function metals, tunable compositions, etc.), suitable semiconductor surface treatments or intentionally changing of the electric field distribution below the interface [2-4]. In this context, many efforts have been dedicated to the basic understanding of the current transport in metal/semiconductor contacts in both lightly and heavily doped epitaxial 4H-SiC layers, to achieve a good control of the properties of this system. While several literature works are devoted to the characterization of Schottky contacts on lightly doped 4H-SiC, basic studies on metal/heavily-doped SiC interfaces have been rather limited so far, in spite of the importance of these systems for the development of SiC devices (e.g. in Ohmic contact regions). In a recent work, *Hara et al.* [5] characterized Schottky diodes fabricated on 4H-SiC epitaxial layers with a doping concentration varying from 6.8×10^{15} up to 1.8×10^{19} cm^{-3}, observing a reduction of the barrier height and an increasing dominance of a thermionic field emission (TFE) mechanism for the current transport with increasing the epilayer doping.

Specifically, heavily doped 4H-SiC layers can be obtained by ion-implantation, which is an essential process for both n-type and p-type selective doping [6]. For instance, metal/semiconductor contacts with Ohmic properties can be obtained on heavily-doped 4H-SiC implanted regions by Ni-based films annealed at high temperature, owing to the formation of nickel silicide (Ni_2Si), as occurring in junction barrier Schottky (JBS) rectifiers technology, where ion-implantation is typically used for selective doping of p^+-type regions [7].

In this work, we focused on the electrical characterization of Ni Schottky contacts onto heavily doped (N_D>10^{19} cm^{-3}) n-type phosphorus-implanted 4H-SiC layer, under forward bias. Specifically, the Schottky properties and the dominant current transport mechanism were highlighted by a detailed electrical characterization of the contact.

Experimental Details

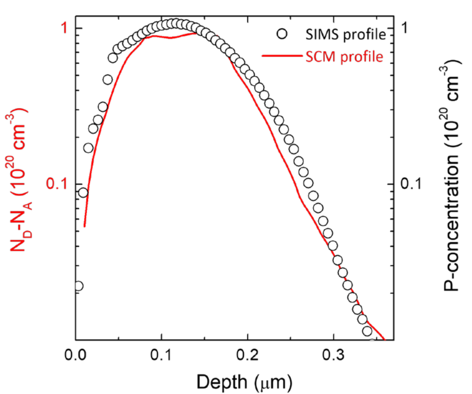

Fig.1: Comparison between the chemical P-profile obtained by SIMS (right scale) and electrically active P-profile derived by SCM (left scale).

N-type 4H-SiC epitaxial layer with nitrogen doping of 1 ×10^{16} cm^{-3}, grown onto a heavily doped 4H-SiC (0001) substrate, was the starting material of our work. The upper part of the epitaxial layer was heavily doped by phosphorus (P)-ion-implantation at 400°C, at energies ranging from 30 to 200 keV and with ion doses between 7.5×10^{13} and 5 ×10^{14} cm^{-2}. The resulting implantation profile extended over 200 nm and with a concentration peak of 1×10^{20} cm^3, as confirmed by previous secondary ion mass spectrometry (SIMS) measurements [8]. A post-implantation thermal annealing treatment, performed at 1675 °C in Ar-ambient and with a carbon capping layer for protecting the sample surface, was able to activate at least 80% of implanted P-ion, as highlighted in Fig.1, which reports the comparison between the SIMS profile and that derived by a depth resolved scanning capacitance microscopy (SCM) analysis (more details in [9]). Moreover, van der Pauw and Hall measurements performed by varying the measurement temperature in the range 300-500K [9], demonstrated that the sheet resistance R_{SH} of the implanted 4H-SiC layer increased with temperature, while an almost constant value was observed for the electron density n_{el} (1.44×10^{15} cm^{-2} at room temperature). These characteristics can be associated to the behavior of a degenerate semiconductor [10] On this material, Schottky barrier diodes were fabricated by depositing 100 nm thick Ni-layer, using a direct current magnetron sputter, and defined by optical lithography and lift-off process in circular structures with radius of 250 μm. A large-area back-side contact was fabricated by Ni-deposition followed by rapid thermal annealing at 950 °C in N_2-atmosphere before the front-side processing [11]. To avoid any consumption of the SiC layer, these Ni-Schottky contacts were deliberately not subjected to annealing treatments. The Schottky contacts were characterized by current–voltage-temperature (I–V-T) measurements (in the range 25°C–115°C), under forward bias, in a Karl-Suss MicroTec probe station equipped with a parameter analyzer.

Results and Discussion

As starting point, in Fig.2 we compared the room-temperature forward current density–voltage ($J-V_F$) characteristics of Ni Schottky contacts formed on n-type heavily-doped 4H-SiC epilayer and on a reference 4H-SiC epilayer without doping implantation. Evidently, the Ni/heavily doped 4H-SiC contact exhibited a lower turn-on voltage with respect to the reference Ni/4H-SiC contact without implant [12].

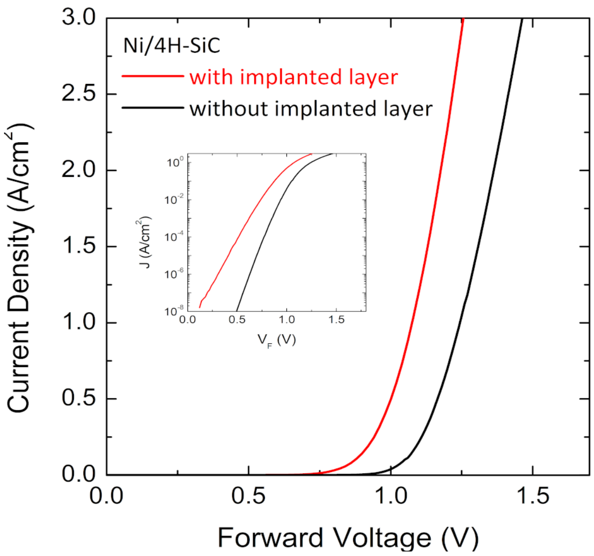

Fig.2: J−VF curves of Ni Schottky contacts on n-type 4H-SiC epilayer with or without n-type implant. In the inset, the same curves in semilog scale.

Typically, the forward characteristics for Schottky contact to 4H-SiC can be described by the thermionic emission (TE) model [13], with J-V_F relationship expressed as

$$J_{TE} = A^*T^2 \times exp\left(-\frac{q\Phi_{B_{TE}}}{k_BT}\right) \times \exp\left(q\frac{V_F - J_{TE}R_{on}}{nk_BT}\right) \tag{1}$$

where A^* is the effective Richardson's constant of 4H-SiC (146 A cm^{-2} K^{-2}) [14], q is the elementary charge, Φ_B is the Schottky barrier, k_B=1.38×10^{-23} J/K is the Boltzmann's constant, T is the absolute temperature, V_F is the voltage applied across the metal/semiconductor interface, R_{ON} is the specific on-resistance and n is the ideality factor. In particular, by analyzing the forward characteristic using the TE model, we derived a barrier height of 0.94 eV and an ideality factor of 1.8, thus showing a high discrepancy from the ideal case for Schottky contact with n=1.

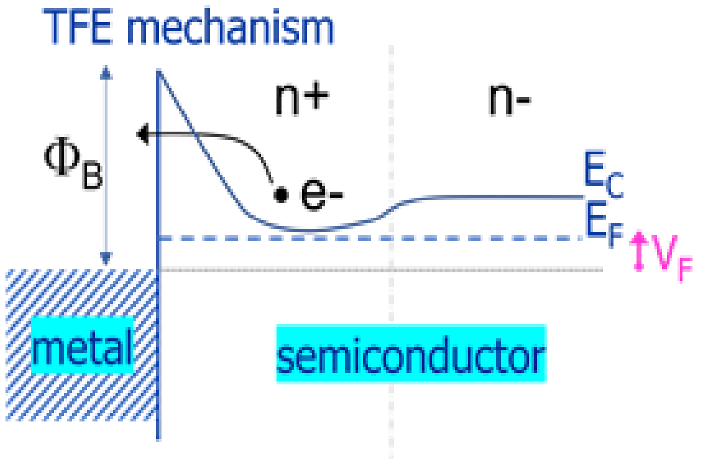

Fig.3: Schematic energy band diagram for the TFE mechanism in a metal/heavily-doped n$^+$-4H-SiC contact under forward bias.

Hence, the current transport through the contact cannot be described by a TE regime. As matter of fact, considering the high doping concentration of the implanted region, a tunneling contribution to the current must be taken into account, as described by the thermionic field emission (TFE) model [15] (Fig.3). The TFE J-V relationship is given by

$$J_{TFE} = J_{0,TFE}(V_F) \times \exp\left(q\frac{V_F - J_{TFE}R_{on}}{E_0}\right) \tag{2}$$

where the saturation current $J_{0,TFE}$ (V_F) can be expressed as

$$J_{0,TFE}(V_F) = \frac{A^{**}T}{k_B cosh(qE_{00}/k_BT)} \times \sqrt{\pi E_{00}\left(\phi_{B_{TFE}} - \Delta E_F - (V_F - J_{TFE}R_{ON})\right)} \times \exp\left(-\frac{q\Delta E_F}{k_BT} - \frac{\phi_{B_{TFE}}-\Delta E_F}{E_0}\right) \quad (3)$$

with ΔE_F the difference between the bottom of the conduction band and the semiconductor Fermi level, $E_0 = E_{00} \times coth\left(\frac{qE_{00}}{k_BT}\right)$ and $E_{00} = \frac{h}{4\pi} \times \sqrt{\frac{N_D}{m^* \varepsilon_{SiC}}}$, where $m^* = 0.38\ m_0$ the effective mass (m_0 is the electron mass) and $\varepsilon_{SiC} = 9.66\ \varepsilon_0$ the dielectric constant of the semiconductor (ε_0 is the vacuum permittivity).

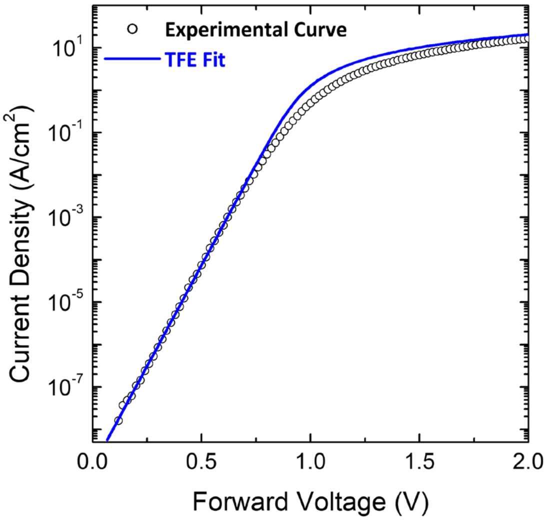

Fig.4: Experimental room-temperature J−VF curve (open symbols) for Ni/heavily doped 4H-SiC Schottky diode and fitting curve according to the TFE model (continuous line).

Fig.4 reports in a semilog scale the experimental room-tempertaure J-V_F curve related to a representative diode on heavily doped 4H-SiC layer, fitted to a simulated TFE curve. The barrier Φ_B and the doping concentration N_D were determined as best-fit parameters of the TFE curve, obtaining Φ_B=1.77 eV and N_D=1.97×10^{19} cm^{-3}. Notably, the ratio k_BT/qE_{00} gives an indication about the relevance of the TE process with respect to the tunneling one. Using N_D=1.97×$10^{19}cm^{-3}$ derived from the fit, we obtained a ratio k_BT/qE_{00} of 0.61, which confirmed the appropriateness of the TFE model [16]. By knowing the doping concentration, the depletion width W_D at the Ni/4H-SiC interface can be derived, resulting of 10 nm for N_D=1.97×10^{19} cm^{-3} [17]. Such finding is in agreement with the value measured by SCM for the active dopant profile (Fig.1) [9]. Under reverse bias the contact showed a leakage current level varying from 10^{-8} up to 10^1 A/cm^2 in the 0-8V range, as discussed in [12]. In order to gain insights on the Schottky barrier properties, the temperature-dependence of the forward characteristics of the diode was studied. As shown in Fig.5, the forward J-V_F characteristics were acquired between 25 °C and 115 °C, showing an increase of the current with the temperature. The experimental curves were then fitted to TFE model for each temperature, obtaing the T-dependence of the barrier height Φ_B and doping concentration N_D, reported in Figs. 6a and 6b, respectively. Specifically, the barrier Φ_B decreased from 1.77 to 1.66 eV with increasing temperature, while an almost constant value of doping at around N_D

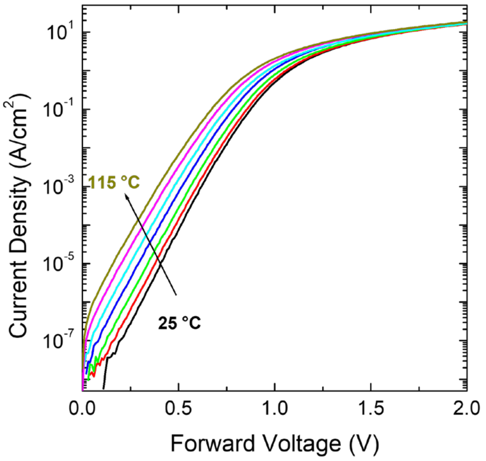

Fig.5: Experimental forward J-V_F curves for Ni/n-type implanted 4H-SiC Schottky diode at T varying from 25 to 115°C.

(1.96±0.02) $\times 10^{19}$ cm^{-3} was found over the measurement temperature range. This latter agrees with SCM profiling measurement related to the electrically active P-ion concentration underneath the interface and with Hall measurements that in the same range of temperature gave an almost constant value for the average carrier concentration over the entire implanted thickness.

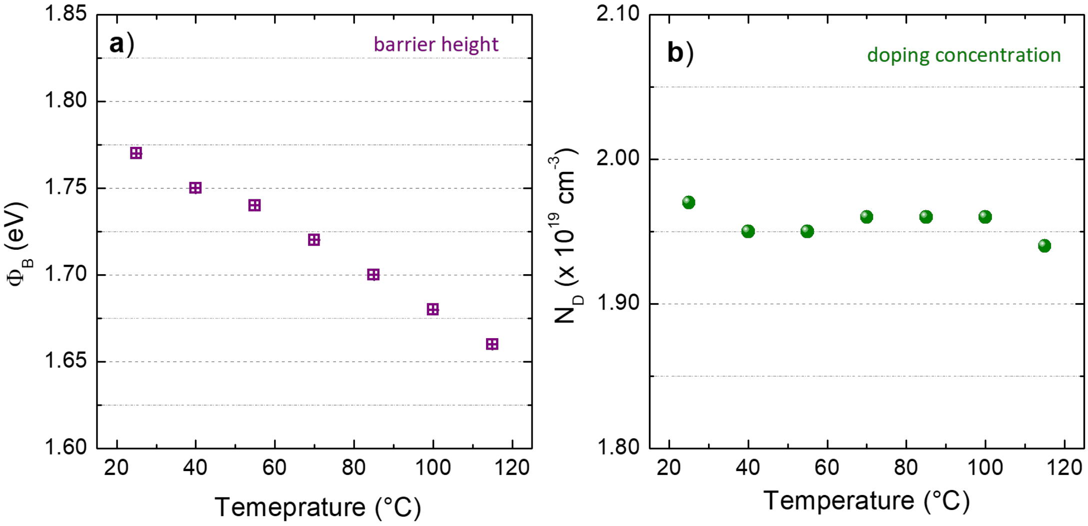

Fig.6: T-dependence of Φ_B and doping concentration, derived by the TFE fits of the forward J-V_F curves.

Summary

In conclusion, we have electrically characterized Ni Schottky contact on n-type-implanted 4H-SiC layer, with doping concentration $N_D > 10^{19}$ cm^{-3}. This ion-implantation doping produced a reduced forward turn-on voltage in the heavily-doped 4H-SiC diode with respect to a reference one. The thermionic-field-emission was the dominant mechanism for the current transport through the interface under forward bias. The temperature analysis of the forward current-voltage curves highlighted a reduction of the Schottky barrier (from 1.77 to 1.66 eV), while the doping concentration maintained constant around 1.96×10^{19} cm^{-3}, in the investigate temperature range 25-115°C. This study provides useful insights for a deeper comprehension of the electrical behavior of Ni contacts and can have possible applications in 4H-SiC Schottky diode technology.

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