Richardson's constant in inhomogeneous silicon carbide Schottky contacts

Fabrizio Roccaforte,[a)] Francesco La Via, and Vito Raineri
CNR-IMM, sezione di Catania, Stradale Primosole 50, I-95121 Catania, Italy

Roberto Pierobon and Enrico Zanoni
Department of Information Engineering, University of Padova, via Gradenigo 6B, I-35131, Padova, Italy

(Received 20 January 2003; accepted 21 March 2003)

The electrical characterization of nickel silicide Schottky contacts on silicon carbide (4H–SiC) is reported in this article. In spite of the nearly ideal behavior of the contact at room temperature ($n=1.05$), the electrical behavior monitored in a wide temperature range exhibited a deviation from the ideality at lower temperatures, thus suggesting that an inhomogeneous barrier has actually formed. A description of the experimental results by the Tung's model, i.e., considering an effective area of the inhomogeneous contact, provided a procedure for a correct determination of the Richardson's constant A^{**}. An effective area lower than the geometric area of the diode is responsible for the commonly observed discrepancy in the experimental values of A^{**} from its theoretical value in silicon carbide. The same method was applied to Ti/4H–SiC contacts. [DOI: 10.1063/1.1573750]

I. INTRODUCTION

Among the wide band-gap semiconductors, silicon carbide (SiC) is going to be used for high-power electronics applications because of its unique physical properties, such as a high critical electric field, a high thermal conductivity, and a high saturated electron velocity.[1] It is already commercially available in high-quality large diameter (up to 75 mm) wafers.

Several studies concerning both ohmic and rectifying contacts on SiC have been performed in the last decade in order to understand the physical mechanism of current transport and, ultimately, to find the optimal conditions for specific applications.[2–4] However, the fabrication of diodes and devices for industrial use imposes the complete understanding of all the technological processes to solve either design and yield related problems.

In particular, many factors may affect the Schottky barrier height Φ_B (SBH) in rectifying contacts on SiC, all concerning the control of the surface preparation prior to metal deposition. Indeed, the electrical behavior of a Schottky contact has been observed to be strongly dependent on the quality of the metal/semiconductor interface.[5,6] Inhomogeneities and/or residual processing-induced contamination in the interfacial region are commonly the reason for deviations from the ideal behavior in the electrical characteristics of Schottky contacts on SiC. The presence of an inhomogeneous Schottky barrier may translate into an undesired anomalous current–voltage ($I-V$) behavior, which is often characterized by an excess of forward current at low-voltage levels. To date, some efforts have been devoted to explain and model, by using different approaches, the experimentally observed anomalies in the $I-V$ characteristics of nonideal Schottky contacts on both 6H– and 4H–silicon carbide.

A simple way to describe this behavior is by using a model of two different SBHs connected in parallel, as reported by Defives *et al*.[7] for Ti/4H–SiC contacts, who divided the total thermoionic current into two independent contributions, weighted by the fraction of the whole diode area covered by each barrier.

However, a bare parallel conduction model can lead to significant error when the SBH presents spatial inhomogeneities on a scale length comparable with the depletion width. In this case, a more accurate approach was given by Tung,[8] who described the nonideal behavior of a metal/semiconductor contact by an inhomogeneous Schottky barrier. Tung's model provides for a more complete treatment of the problem since it takes into account the possible presence of a distribution of nanometer-size ''patches'' with a lower barrier height embedded in a uniform high barrier background. Under certain conditions, the potential distribution below these patches, and hence the current flow through the contact, can be affected by the ''pinch-off'' effect of the low barrier regions by the surrounding average uniform high barrier.[8] This approach also allows one to explain a large series of abnormal experimental results on ''real'' Schottky contacts,[9] which in turn cannot be described by a simple parallel conduction model.

In 4H–SiC, Tung's model was recently used by Im *et al*.[10] to describe the behavior of nonideal Pd/6H–SiC barriers, who experimentally demonstrated the presence of a nanometer scale distribution of a SBH by means of ballistic electron emission microscopy (BEEM)[11] and compared these results with the macroscopic electrical characteristics of the diodes. Beyond the technological importance related to the possibility of achieving a good metal/semiconductor contact quality and hence the reliability of the device performance,

[a)]Electronic mail: fabrizio.roccaforte@imm.cnr.it

all of these works are an interesting survey on the physical mechanism of current transport.

Nickel, together with titanium, is one of the most commonly used metals for the formation of rectifying contacts on SiC.[12] However, experimental works performed on Ni/SiC Schottky diodes often showed a nonideal behavior of the forward $I-V$ characteristics along with a strong dependence of the values of Φ_B on the surface preparation conditions.[13–15] This problem, however, can be overcome by inducing nickel silicide (Ni_2Si) formation upon annealing at temperatures above 600 °C, which consumes a 4H–SiC layer by solid-state reaction, thus giving rise to an interface at a larger depth inside the material. In this way, a nearly ideal behavior of the contact is obtained, independent of the surface preparation.[15]

Although in many works, almost ideal ($n<1.1$) Schottky contacts on SiC have been demonstrated, the value of Richardson's constant A^{**} determined from the electrical characterization, which is an important physical parameter for the current transport, was often found to be significantly lower than the theoretical one.[13,16,17] None of these works, however, reported in detail on the possible reasons for this finding. Therefore, the aim of this article is to explain the discrepancy between the experimental values of A^{**} and the theoretical one in 4H–SiC.

In this article, the electrical forward ($I-V$) characterization of Ni_2Si Schottky contacts on 4H–SiC are reported. These electrical measurements showed a dependence on the temperature of the ideality factor n and the SBH Φ_B that cannot be explained by the classical theory. The explanation of the experimental results by means of Tung's model[8] provided a method for a correct determination of the Richardson's constant. In this view, the commonly observed underestimation of the value of A^{**} could be attributed to an effective area, involved in the current transport, which may be significantly lower than the geometric area of the diode. The procedure was verified also for Ti/4H–SiC Schottky contacts.

II. EXPERIMENTAL DETAILS

Measurements on several batches of SiC Schottky diodes led us to systematically observe an underestimation of the Richardson's constant with respect to the theoretical value.[16,17] An electrical characterization of these diodes and the structural characterization of the metallization layer forming the Schottky contact have been performed in the past and are reported elsewhere.[15–17]

Hence, to understand the reason for this deviation, circular Schottky diodes, with a radius of 420 μm, were intentionally fabricated on high-quality 4H−SiC (0001) epitaxial wafers purchased from CREE, using Ni_2Si as Schottky barrier and an optimized processing to obtain an ideality factor close to unity and a large reproducibility of the electrical characteristics.[15]

Both the epitaxial layer and the heavily doped substrate were n-type doped with concentrations of $N_D=1\times10^{16}\,\mathrm{cm}^{-3}$ and $N_D=5\times10^{18}\,\mathrm{cm}^{-3}$, respectively. A low resistance ohmic contact was formed on the wafer rear by rapid thermal annealing (RTA) at 950 °C in N_2 of a 100 nm thick nickel film, deposited in a ultrahigh vacuum electron-beam evaporation chamber. The Schottky barrier on the wafer front side was formed by deposition of 200 nm nickel film followed by RTA in N_2 at 700 °C. Prior to Schottky contact deposition, sacrificial oxidation of the sample was performed, followed by oxide removal in buffered HF and solvent ultrasonic bath cleaning. The diodes were finally assembled in a standard package.

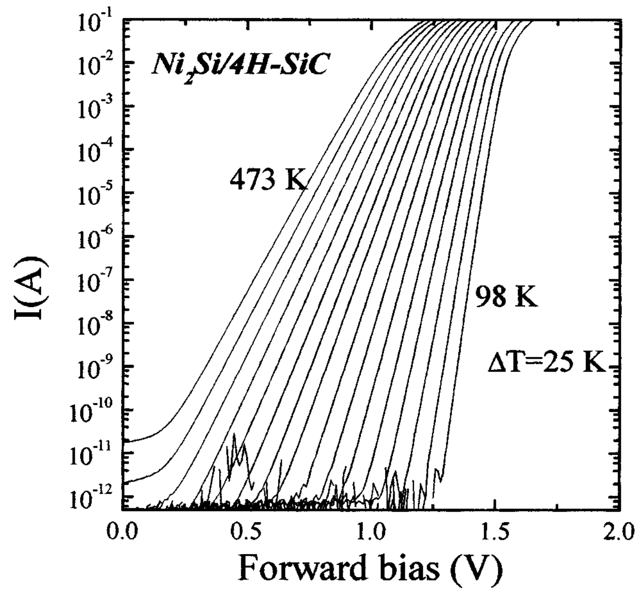

FIG. 1. Forward $I-V$ characteristics of Ni_2Si/4H−SiC diodes at different temperatures between 98 and 473 K. The measurements were carried out with a temperature step of 25 K.

For comparison, Schottky rectifiers with a commercial standard titanium Schottky metallization, having approximately the same contact area as the Ni_2Si diodes, were also characterized in order to verify the validity of our procedure. $I-V$ characterization, obtained using a Semiconductor Parameter Analyzer HP 4142B, was carried out at different temperatures, ranging between 98 K and 473 K, by using an Environmental Test Chamber Delta 9023 for controlling the device temperature.

III. RESULTS AND DISCUSSION

The $I-V$ characterization of the Schottky diodes under forward bias was performed in order to determine the significant parameters ruling the current transport across the metal/SiC contact, namely, the ideality factor n and the Schottky barrier height Φ_B. Figure 1 shows the semilogarithmic plot of the $I-V$ curves of the Ni_2Si/4H−SiC diodes under forward bias. The curves were acquired in the range 98 – 473 K, with a temperature step of 25 K.

A set of 40 diodes was characterized at room temperature, exhibiting a linear region over eight orders of magnitudes with a full width at half maximum of the distribution of the ideality factors of 0.05. The experimental $I-V$ curves reported in Fig. 1 were chosen as representative of the general electrical trend of the contact. In the following, the errors attributed to the physical parameters extracted by our

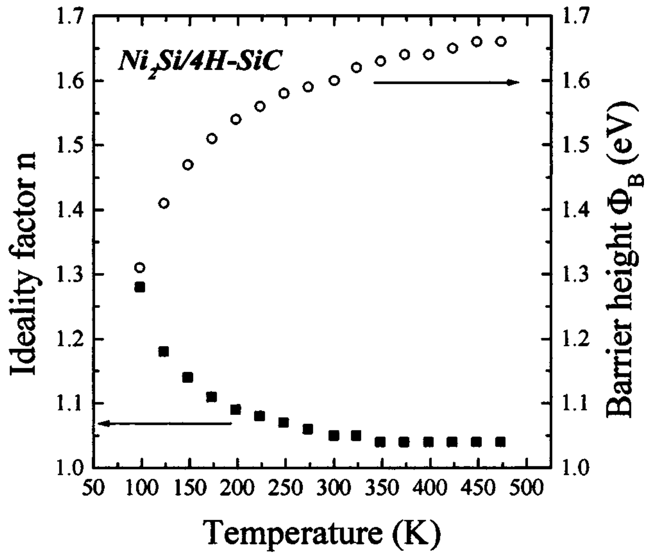

FIG. 2. Ideality factor n and Schottky barrier height Φ_B as function of the absolute temperature for Ni_2Si/4H−SiC. The ideality factor n decreases, while the value of Φ_B increases by increasing temperature.

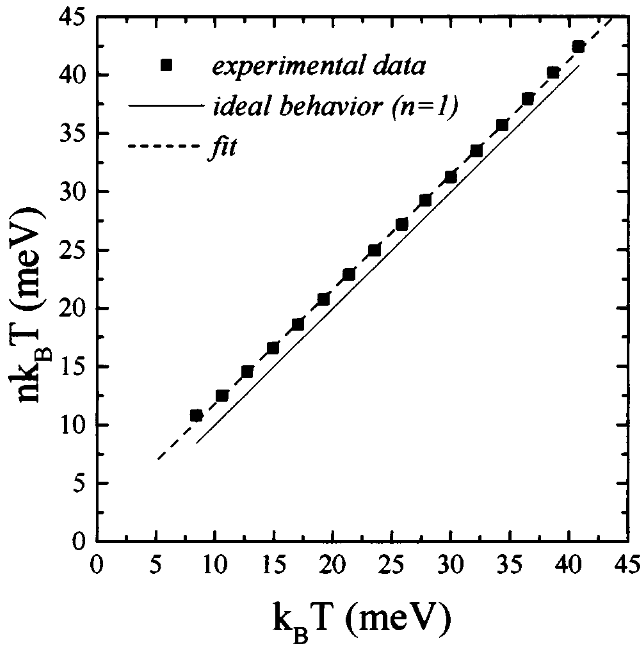

FIG. 3. Plot of nk_BT as a function of k_BT showing the T_0 anomaly $n\sim 1+T_0/T$. The linear fit of the data is also reported, from which a value of $T_0=23$ K was calculated. For reference, the straight line of the ideal behavior $n=1$ is also reported.

analysis (n, Φ_B, A^{**}) were calculated by the errors of slopes and intercepts of the linear fits. The ideality factor n and the Schottky barrier height Φ_B were determined by fitting the linear region of the forward $I-V$ curves reported in Fig. 1, according to the thermoionic emission theory, i.e., to the relation

$$I=SA^{**}T^2e^{\frac{-q\Phi_B}{k_BT}}(e^{\frac{qV}{nk_BT}}-1)=I_S(e^{\frac{qV}{nk_BT}}-1), \tag{1}$$

where S is the area of the diode, A^{**} is the effective Richardson's constant, k_B is the Boltzmann's constant, q is the electron charge and T is the absolute temperature.[18]

For this calculation, we used the theoretical value of A^{**} for 4H−SiC ($146\ \mathrm{A/cm^2\,K^2}$), [19] which was determined by using a value of the effective mass of $0.2m_0$ (Ref. 20) and six conduction band minima.[21] At room temperature, the barrier height of Ni_2Si on 4H–SiC was $\Phi_B=1.60$ eV and the ideality factor $n=1.05$.

Both the ideality factor n and the barrier height Φ_B are reported in Fig. 2 as a function of the absolute temperature T. As can be clearly seen, these parameters are both temperature dependent. In particular, by decreasing temperatures the ideality factor deviates from the unity ($n=1.04\pm 0.02$ at 473 K and 1.28 ± 0.08 at 98 K), whereas Φ_B decreases from the value of 1.66 ± 0.01 eV at 473 K to 1.31 ± 0.01 eV at 98 K.

Therefore, in spite of the almost ideal behavior of the Ni_2Si/SiC contact observed at room temperature ($n=1.05$), the deviation from the ideality observed at lower temperatures suggests that an inhomogeneous barrier has actually formed. Indeed, the presence of barrier inhomogeneities was already experimentally demonstrated by Im *et al.*[10] in 4H–SiC contacts and correlated to the macroscopic electrical behavior by using the model of Tung.[8] Moreover, other experimental works proved the validity of Tung's model[8] on intentionally inhomogeneous fabricated Schottky barriers.[22–24] Hence, on the basis of these previous experimental results and of the temperature dependence of n and Φ_B (see Fig. 2), we can reasonably ascribe the electrical behavior of our Ni_2Si/4H−SiC contacts to the presence of an inhomogeneous Schottky barrier.

In order to gain insight into the Schottky barrier and further justify the possibility of applying Tung's model[8] to our data, the temperature dependence of the ideality factor n was reported in a plot of nk_BT versus k_BT. This plot is shown in Fig. 3, in which the straight line representing the ideal behavior of a Schottky contact (i.e., with $n=1$) is also reported as reference. The experimental data could be fitted by a straight line, which is parallel to that of the ideal Schottky contact behavior. The latter means that the ideality factor can be expressed in the form $n\sim 1+T_0/T$, with $T_0=23\pm 2$ K in our case, as determined by the fit parameters. This behavior, which is commonly referred as the "T_0 anomaly", is typical of a real Schottky contact, i.e., a contact with a distribution of barrier ihnomogeneities.[9] Accordingly, the behavior of our Ni_2Si/4H−SiC contact can be described by an "effective" barrier, lower than the average Schottky barrier of the ideal Ni_2Si contact.[8,9] The determination of the value of the effective barrier height was possible by the electrical characterization of the contact at different temperatures, by means of the "conventional" Richardson's plot. In fact, from relation (1), for almost ideal contacts, the plot of the $\ln(I_s/T^2)$ as a function of $1/k_BT$ allows the determination of the effective SBH and of the product (SA^{**}).

In Fig. 4, the Richardson's plot of our data is reported, in which the saturation current I_s was determined from the extrapolation at V=0 of the linear fit of the $I-V$ curves in the range 300–473 K, i.e., where the deviation from the ideality is small ($n\sim 1.04$). From the slope of the linear fit of the data, an effective barrier height of 1.50 ± 0.01 eV was found, while a value of the product $SA^{**}=(1.45\pm 0.47)$

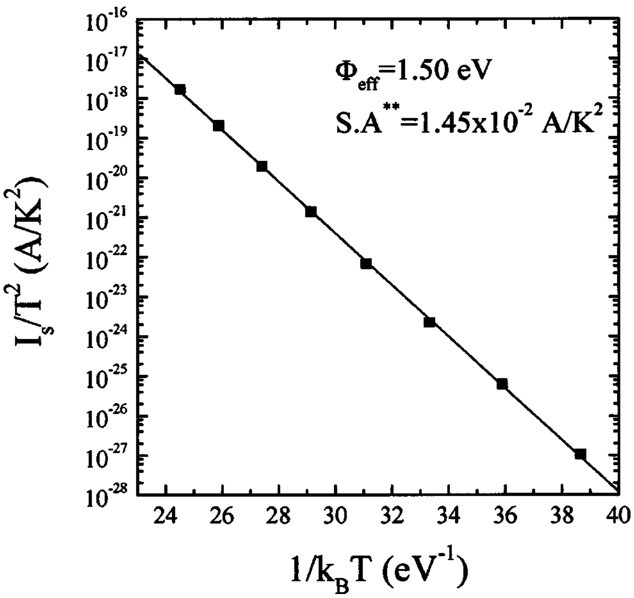

FIG. 4. Richardson plot $\ln(I_s/T^2)$ vs $1/k_BT$. From the slope of the linear fit of the data, an effective SBH of 1.50 eV was determined.

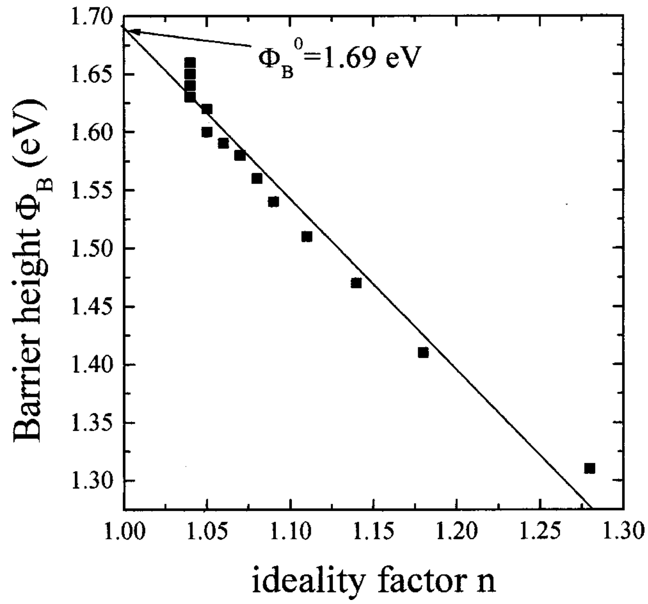

FIG. 5. Schottky barrier height Φ_B versus ideality factor n. The extrapolation at $n=1$ of the linear fit of the data gave a value of the average barrier $\Phi_B^0=1.69$ eV.

$\times 10^{-2}$ A/K^2 was determined from the intercept. This method takes into account the average behavior of the contact at different temperatures. Hence, the SBH value determined from the *slope* of the Richardson's plot is regarded as the effective barrier. Its value is independent of the contact area S, contrary to that extracted from the y-axis *intercept* of the linear fit of ln(I) versus V, i.e., $\Phi_B=k_BT/q[\ln(A^{**}ST^2)-(\text{intercept})]$.

As a matter of fact, the value of 1.50 eV is intermediate between the value obtained at high temperatures (1.66 eV) and that found at low temperatures (1.31 eV). This experimental evidence agrees with the theoretical considerations, predicting that the effective barrier Φ_{eff}, which characterizes an inhomogeneous contact, is smaller than that of a spatially homogeneous large barrier Φ_B^0.[8,9] In such a contact at high temperatures, the current transport is dominated by the uniform average barrier of Ni_2Si, while by decreasing temperatures, the presence of inhomogeneities with a lower barrier becomes dominant. From the y-axis intercept of the linear fit reported in Fig. 4, by using the geometric area of the diode, a value of $A^{**}=2.6\pm 0.8$ A/cm^2 K^2 was found. Then, the value of A^{**} extracted by the $I(T)$ data is more than a factor of 50 lower with respect to the theoretical value of 146 A/cm^2 K^2 for 4H–SiC.

The average barrier height Φ_B^0 of the uniform Ni_2Si, which dominates the current flow at high temperatures, could be determined by analyzing the correlation existing between the ideality factor and the barrier height as determined from the $I-V$ curves.

This correlation is clearly shown in Fig. 5, in which the values of Φ_B are reported as a function of n. The data can be satisfyingly described by a linear relation. Schmitdorf *et al.*,[25] starting from Tung's theory,[8] ascribed this behavior to deviations of the SBH from the characteristic value of a uniform interface. Even Tung[26] admitted that his model may justify a linear relation between the SBH and n, consistently with the ideal behavior of nonuniform barriers observed in the high-temperature limit. Accordingly, the average barrier height Φ_B^0 (i.e., the value which is expected for an homogeneous ideal contact), can be found by the asymptotic value of the barrier extrapolated at $n=1$.[25] By the extrapolation of Φ_B at $n=1$ of the experimental data reported in Fig. 5, a value of $\Phi_B^0=1.69$ eV was determined. This value is slightly higher than the value of Φ_B determined by the $I-V$ curve at 473 K. According to the Tung's model,[8] the effective Schottky barrier height Φ_{eff} and the average barrier height Φ_B^0 of the metal/semiconductor contact are connected by

$$\phi_{\text{eff}}=\phi_B^0-\gamma\left(\frac{V_{\text{bb}}}{\eta}\right)^{\frac{1}{3}}, \tag{2}$$

where γ is a parameter which is introduced to describe the inhomogeneity of the SBH and includes the dimensions of the patch with a lower barrier and the deviation from the average high barrier Φ_B^0, V_{bb} is the band bending, and $\eta=\varepsilon_s/qN_D$,[9] with ε_s as the permittivity of the material.

Using the value of $\Phi_{\text{eff}}=1.50$ eV extracted from the Richardson's plot shown in Fig. 4, and the value of $\Phi_B^0=1.69$ eV determined by the $I-V$ data with the method proposed in Ref. 25, from Eq. (2) it was possible to give an estimation of $\gamma=1.31\times 10^{-4}$ cm$^{2/3}$ V$^{1/3}$.

For a geometry of low barrier circular patches embedded in a region of high barrier Φ_B^0, the current flowing through the single patch is given by

$$I_{\text{eff}}=A_{\text{eff}}A^{**}T^2e^{-\beta\Phi_{\text{eff}}}(e^{\beta V}-1), \tag{3}$$

where A_{eff} is the effective area of a low barrier patch and $\beta=q/k_BT$.

Here, the effective area of the low SBH patch can be expressed as

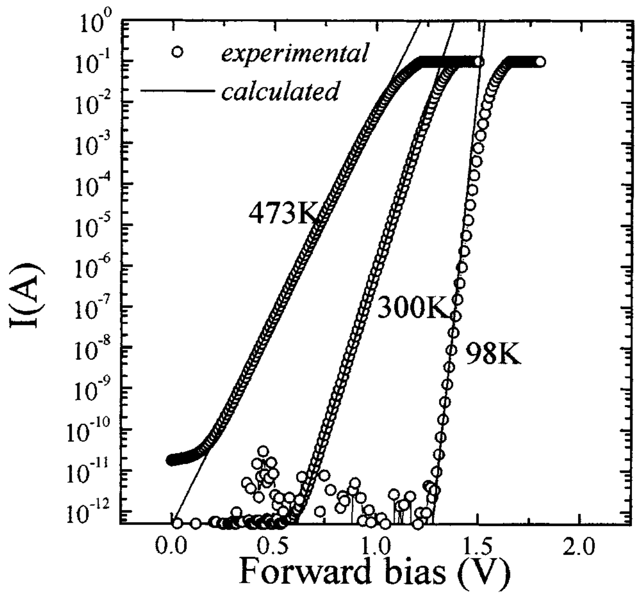

FIG. 6. Experimental $I-V$ plots at the temperatures of 473 K, 300 K, and 98 K, and calculated curves (in the linear region) obtained by applying the Tung's model (see Ref. 8) to the Ni_2Si/4H−SiC contact.

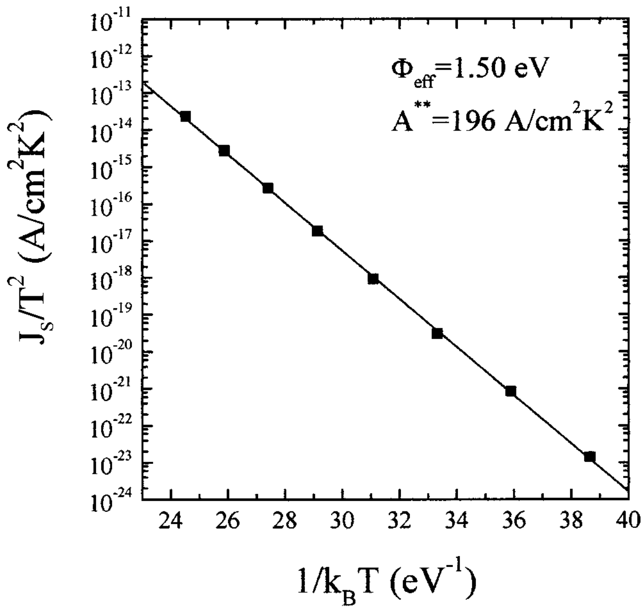

FIG. 7. "Modified" Richardson plot $\ln(J_s/T^2)$ vs $1/k_BT$. The saturation current density J_s was obtained by dividing the experimental values of I_s by the calculated total effective area (NA_{eff}). A value of 196 A/cm^2 K^2 for the Richardson's constant could be determined by the intercept of the linear fit of the data.

$$A_{\text{eff}} = \frac{4\pi\gamma}{9\beta}\left(\frac{\eta}{V_{\text{bb}}}\right)^{2/3}. \tag{4}$$

As an example, using the value of γ determined by the experimental values of Φ_B^0 and Φ_{eff}, a value of $A_{\text{eff}} = 2.46 \times 10^{-12}\,\text{cm}^2$ at room temperature was determined.

The expression of the current flowing through the diode can be obtained by adding the current through the low barrier patches to the current which passes through the surrounding homogeneous regions. However, it is often reasonably assumed that the $I-V$ characteristic is dominated by the current flow through the low SBH patches.[26] In fact, as pointed out by Ohdomari *et al.*,[27] even though the area covered by the low barrier represents only a few percent fraction of the whole contact, the current through a contact is mainly affected by the presence of low barrier regions (since the ratio of the currents is proportional to a Boltzmann factor involving the two barrier heights).

Hence, the current transport can be described by rewriting relation (3) as

$$I = NA_{\text{eff}}A^{**}T^2 e^{-\beta\Phi_{\text{eff}}}(e^{\beta V} - 1), \tag{5}$$

where N is the number of patches covering the area of the diode.

The experimental $I-V$ curves were simultaneously fitted at all the temperatures by using Eq. (5) with the number of patches N as free parameter. A value of $N = 3 \times 10^7$ gave a good fit of the experimental data in the investigated range of temperatures. Obviously, the product (NA_{eff}) represents the total effective area contributing to the current transport. Although N is independent of temperature, as it gives the number of patches in the contact, the product (NA_{eff}) exhibits a temperature dependence, as can be clearly seen from the definition of A_{eff} in Eq. (4).

Figure 6 reports, as an example, the experimental $I-V$ curves at 473 K, 300 K, and 98 K, together with the respective calculated curves obtained by using in Eq. (5) the value of $\Phi_{\text{eff}} = 1.50$ eV and the values of NA_{eff} at each temperature ($1.26 \times 10^{-4}\,\text{cm}^2$, $7.39 \times 10^{-5}\,\text{cm}^2$, and $2.22 \times 10^{-5}\,\text{cm}^2$ at 473, 300, and 98 K, respectively). The excellent agreement between the theory and the experimental data over the entire temperature range demonstrates the consistence of our procedure.

It must be pointed out that, in order to simplify our calculations, a unique value of γ was used instead of a distribution. In fact, a more rigorous calculation would require a distribution of γ's, coherently with the experimentally observed T_0 anomaly behavior (see Fig. 3), which is associated to a distribution of inhomogeneities.[9]

It is worth noting that the total effective area involved in the current transport represents only 1%–2% of the entire geometric area of the contact. Therefore, in order to correctly determine the value of A^{**}, the Richardson plot shown in Fig. 4 must be modified, by substituting the geometric area of the diode with the value of the total effective area of the patches (NA_{eff}).

Since, as already mentioned before, NA_{eff} is temperature dependent, in order to eliminate the temperature dependence from the pre-exponential factor, the $\ln(J_s/T^2)$ versus $1/k_BT$ was reported in the Richardson plot, where $J_s = I_s/NA_{\text{eff}}$.

Figure 7 shows the Richardson's plot, modified in the aforementioned way to take into account the presence of an inhomogeneous barrier. From the slope of the straight line fitting the data, the value of Φ_{eff} was obtained (1.50 eV), while from the intercept, a value of the Richardson's constant of $A^{**} = 196 \pm 60$ A/cm^2 K^2 was determined. The latter, within the error, is in agreement with the theoretical value of 146A/cm^2 K^2.

Some past experimental works by Toyama *et al.*[28,29] also

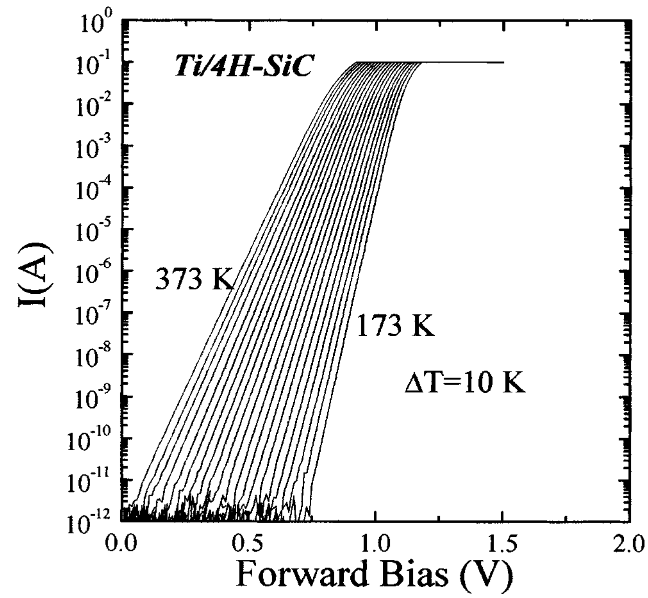

FIG. 8. Forward $I-V$ characteristics of Ti/4H–SiC diodes at different temperatures between 173 and 373 K. The measurements were carried out with a temperature step of 10 K.

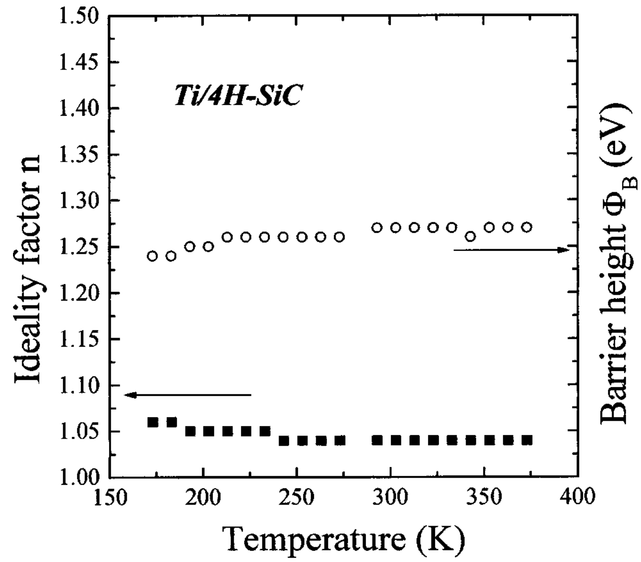

FIG. 9. Ideality factor n and Schottky barrier height Φ_B as function of the absolute temperature for Ti/4H–SiC.

investigated the interesting question of the value of A^{**} in silicon, reporting on deviations of A^{**} from the theoretical value ($112\ \mathrm{A/cm^2\,K^2}$ in Si). In these works, the dependence of A^{**} on the Schottky metal, the film thickness, and the postannealing conditions was investigated, mainly in terms of possible differences in the interface quality determined by deposition parameters and/or annealing treatments. However, a complete electrical $I-V$ characterization as a function of the temperature, which can indicate the presence of low barrier inhomogeneities as in our case, was not reported and, implicitly, in all calculations, the effective area was assumed to be coincident with the geometric area.[29] On the other hand, very small values of A^{**} compared to the theoretical value, determined by Hacke *et al.*[30] in nearly ideal GaN Schottky diodes, were ascribed to the presence of a very thin barrier at the metal/semiconductor junction, through which the electron must tunnel.

In our case, instead, considering the nearly ideal Ni_2Si/4H−SiC contact, actually as an inhomogeneous barrier (i.e., in spite of its ideality factor close to unity at room temperature), allowed us to demonstrate that the effective "active" area may represent only a small fraction of the geometric area of the diode. Therefore, it can be concluded that the presence of an inhomogeneous Schottky barrier, resulting in a reduction of the effective area interested by the current flow, is responsible for the low values of A^{**} often measured in SiC.[13,16,17]

In order to verify the validity of our procedure for the determination of A^{**}, Schottky rectifiers using titanium as Schottky metal were electrically characterized by performing the same data analysis as done for the Ni_2Si diodes. Figure 8 reports the experimental $I-V$ characteristics of Ti/4H–SiC Schottky diodes, measured in the temperature range 173–373 K. At room temperature, the value of the barrier height was 1.27 eV while the ideality factor was $n=1.04$. Obviously, because of the lower barrier height of Ti on 4H–SiC, at a fixed current value and temperature, a lower voltage drop than that of Ni_2Si diodes is observed. By means of Eq. (1) the ideality factor and the Schottky barrier height were determined, and their values are reported in Fig. 9 as a function of the temperature. As can be seen in this case, the values of n deviate less from the ideality in the whole range of temperatures, thus being an indication of the higher uniformity of the Ti/4H–SiC barrier than the Ni_2Si/4H−SiC one.

The extrapolation at $n=1$ of the barrier height value Φ_B^0 for a uniform Ti contact was 1.31 eV. By the standard Richardson's plot, a value of effective barrier $\Phi_{\mathrm{eff}}=1.22\pm0.01$ eV and of the Richardson's constant $A^{**}=22\pm4\ \mathrm{A/cm^2\,K^2}$ were extracted, the latter being about a factor of 10 higher than that found for Ni_2Si ($2.6\ \mathrm{A/cm^2\,K^2}$).

Considering its different values determined by $I-V$ characterization for Ni_2Si and for Ti contacts, it can be argued that A^{**} is very sensitive to the condition of the interface, in spite of the conventional predictions of a constant value, independent of the metal. In particular, the higher value of A^{**} found for Ti/4H–SiC compared to that found in Ni_2Si/SiC contacts is consistent with a more uniform Schottky barrier, as is also demonstrated by the different trend of the ideality factor as a function of temperature (see Figs. 2 and 9). In spite of the low ideality factor in a wide temperature range, however, also for Ti contacts, the value of A^{**} is still more than a factor of 5 lower than the theoretical value. Also in the case of the Ti/4H–SiC contact, the experimental data were described by an inhomogeneous barrier, by the procedure already used in the case of Ni_2Si contacts.

From the values of $\Phi_{\mathrm{eff}}=1.22$ eV and $\Phi_B^0=1.31$ eV, using Eq. (2), a value of $\gamma=7.05\times10^{-5}\ \mathrm{cm^{2/3}\,V^{1/3}}$ was found. Substituting these values in Eq. (4), the experimental $I-V$ curves were fitted in the whole temperature range with a value of $N=6\times10^8$. Hence, the Richardson constant was determined by correcting the conventional method, i.e., using

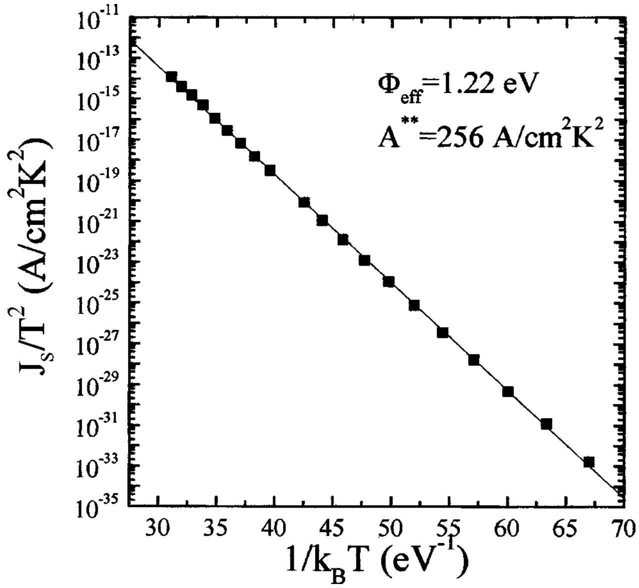

FIG. 10. "Modified" Richardson plot $\ln(J_s/T^2)$ vs $1/k_BT$ for the Ti/4H–SiC contact, from which a value of $A^{**}=256\ \mathrm{A/cm^2\,K^2}$ could be determined.

the values of A_{eff} determined by fitting the experimental data with the Tung's model.[8] Figure 10 shows the modified Richardson's plot for the Ti/4H–SiC contact. From the intercept of the linear fit of the data, a value of $A^{**}=256 \pm 51\ \mathrm{A/cm^2\,K^2}$ was extracted. This value is in satisfactory agreement with that found for the Ni_2Si contact with the same procedure. Therefore, it can be concluded that taking into account the deviation from the ideality of SiC Schottky contacts (by means of Tung's model)[8] allows one to obtain a Richardson's constant independent of the Schottky metal, as predicted by theory.

Some final physical considerations concerning our results must be done. Although both in the case of Ni_2Si and Ti, our contacts showed the typical features of an inhomogeneous Schottky barrier, apart from the electrical $I-V$ data, it was not possible for us to directly detect these inhomogeneities. The latter, in fact, requires nanometer-scale sensitive techniques like BEEM, as already demonstrated elsewhere.[10] However, from our analysis it is clear that the state of the metal/SiC interface (which translates into an effective contact area) is ultimately responsible for the underestimation of the value of A^{**}. In particular, in the case of Ni_2Si, it is possible that the annealing temperature used for silicidation (700 °C) did not lead to the complete transformation of nickel into the Ni_2Si phase. Previous works on 6H– and 4H–SiC, in fact, showed the coexistence of two different phases ($Ni_{31}Si_{12}$ and Ni_2Si) upon annealing at 600 °C,[15,31] thus leading to an inhomogeneous barrier. On the other hand, in the case of Ti contacts, it cannot be excluded that a better interfacial quality, due to the capability of Ti of growing epitaxially on hexagonal SiC,[32] results in a more uniform barrier, as experimentally observed from the more regular temperature behavior of the ideality factor.

IV. CONCLUSIONS

In this article, the electrical characterization of the Ni_2Si/4H–SiC Schottky contact was reported. The temperature dependence of the ideality factor and of the SBH suggested the occurrence of an inhomogeneous barrier, in spite of the nearly ideal behavior of the contact at room temperature. The experimental data were described by the Tung's model,[8] and this procedure, in turn, enabled the correct determination of the Richardson constant, in satisfying agreement with the theoretical value. The same value of A^{**} was found by applying this method to a different metal/SiC contact (Ti/4H–SiC). The underestimation of the Richardson's contact in SiC, often reported in literature, can then be attributed to an effective area involved in the current transport which may be significantly lower than the geometric area of the contact, thus finding its ultimate physical reason in the quality of the metal semiconductor/interface. The more plausible causes may be indicated in the presence of surface defects in the material, interface roughness (e.g., due to Ni_2Si silicidation) and processing-induced contaminations of the surface.

ACKNOWLEDGMENTS

The authors thank Salvatore Di Franco for his valuable collaboration during the fabrication of Schottky diodes.

[1] Y. S. Park, SiC Materials and Devices, Semiconductors and Semimetal Vol. 52, edited by R. K. Willardson and E. R. Weber, (Academic, San Diego, 1998).
[2] J. R. Waldrop, R. W. Grant, Y. C. Wang, and R. F. Davies, J. Appl. Phys. **72**, 4757 (1992).
[3] L. M. Porter and R. F. Davies, Mater. Sci. Eng., B **34**, 83 (1995).
[4] M. J. Bozack, Phys. Status Solidi B **202**, 549 (1997).
[5] M. Bhatnagar, B. J. Baliga, H. R. Kirk, and G. A. Rozgonyi, IEEE Trans. Electron Devices **43**, 150 (1996).
[6] B. J. Skromme, E. Luckowski, K. Moore, M. Bhatnagar, C. E. Weitzel, T. Gehoski, and D. Ganser, J. Electron. Mater. **29**, 376 (2000).
[7] D. Defives, O. Noblanc, C. Dua, C. Brylinski, M. Barthula, V. Aubry-Fortuna, and F. Meyer, IEEE Trans. Electron Devices **46**, 449 (1999).
[8] R. T. Tung, Phys. Rev. B **45**, 13509 (1992).
[9] J. Sullivan, R. T. Tung, M. Pinto, and W. R. Graham, J. Appl. Phys. **70**, 7403 (1991).
[10] H. J. Im, Y. Ding, J. P. Pelz, and W. J. Choyke, Phys. Rev. B **64**, 075310 (2001).
[11] L. D. Bell, and W. J. Kaiser, Phys. Rev. Lett. **61**, 2368 (1988).
[12] K. J. Schoen, J. M. Woodall, J. A. Cooper, and M. R. Melloch, IEEE Trans. Electron Devices **45**, 1595 (1998).
[13] V. Saxena, J. N. Su, and A. J. Steckl, IEEE Trans. Electron Devices **46**, 456 (1999).
[14] C. Raynaud, K. Isoird, M. Lazar, C. M. Johnson, and N. Wright, J. Appl. Phys. **91**, 9841 (2002).
[15] F. Roccaforte, F. La Via, V. Raineri, L. Calcagno, P. Musumeci, and G. G. Condorelli, Appl. Phys. A: Mater. Sci. Process. published online 17 Dec. 2002, DOI: 10.1007/s00339-002-1981-8.
[16] F. La Via, F. Roccaforte, A. Makhtari, V. Raineri, P. Musumeci, and L. Calcagno, Microelectron. Eng. **60**, 269 (2002).
[17] F. Roccaforte, F. La Via, A. La Magna, S. Di Franco, and V. Raineri, (unpublished).
[18] E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contact* (Oxford Science, Oxford, 1988).
[19] A. Itoh, T. Kimoto, and H. Matsunami, IEEE Electron Device Lett. **16**, 280 (1995).
[20] W. Götz, A. Schöner, G. Pensl, W. Suttrop, W. J. Choyke, R. Stein, and S. Leibenzeder, J. Appl. Phys. **73**, 3332 (1992).
[21] Y. M. Tairov and Y. A. Vodakov, *Electroluminescence*, edited by J. I. Pankove (Springer, New York, 1977), pp. 31–61.
[22] S. Anand, S. B. Carlsson, K. Deppert, L. Montelius, and L. Samuelson, J. Vac. Sci. Technol. B **14**, 2794 (1996).
[23] A. Olbrich, J. Vancea, F. Kreupl, and H. Hoffmann, J. Appl. Phys. **83**, 358 (1998).
[24] R. C. Rossi and N. S. Lewis, J. Phys. Chem. B **105**, 12303 (2001).

[25] R. F. Schmitsdorf, T. U. Kampen, and W. Mönch, J. Vac. Sci. Technol. B **15**, 1221 (1997).
[26] R. T. Tung, Mater. Sci. Eng., R. **35**, 1 (2001).
[27] I. Ohdomari, T. S. Kuan, and K. N. Tu, J. Appl. Phys. **50**, 7020 (1979).
[28] N. Toyama, T. Takahashi, H. Murakami, and H. Koriyama, Appl. Phys. Lett. **46**, 557 (1985).
[29] N. Toyama, J. Appl. Phys. **63**, 2720 (1988).
[30] P. Hacke, T. Detchprohm, K. Hiramatsu, and N. Sawaki, Appl. Phys. Lett. **63**, 2676 (1993).
[31] S. Y. Han and J.-L. Lee, J. Electrochem. Soc. **149**, G189 (2002).
[32] L. M. Porter, R. F. Davies, J. S. Bow, M. J. Kim, R. W. Carpenter, and R. C. Glass, J. Mater. Res. **10**, 688 (1995).