Annealing temperature influence on the degree of inhomogeneity of the Schottky barrier in Ti/4H–SiC contacts*

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(Received 2 April 2014; revised manuscript received 9 July 2014; published online 10 October 2014)

Tung's model was used to analyze anomalies observed in Ti/SiC Schottky contacts. The degree of the inhomogeneous Schottky barrier after annealing at different temperatures is characterized by the 'T_0 anomaly' and the difference ($\Delta\Phi$) between the uniformly high barrier height (Φ_B^0) and the effective barrier height (Φ_B^{eff}). Those two parameters of Ti Schottky contacts on 4H–SiC were deduced from I–V measurements in the temperature range of 298 K–503 K. The increase in Schottky barrier (SB) height (Φ_B) and decrease in the ideality factor (n) with an increase measurement temperature indicate the presence of an inhomogeneous SB. The degree of inhomogeneity of the Schottky barrier depends on the annealing temperature, and it is at its lowest for 500-°C thermal treatment. The degree of inhomogeneity of the SB could reveal effects of thermal treatments on Schottky contacts in other aspects.

Keywords: Schottky contact, SiC, inhomogeneity barrier

PACS: 73.40.Ns **DOI:** 10.1088/1674-1056/23/12/127302

1. Introduction

Silicon carbide (SiC) is a promising semiconductor material for fabrication of high-power, high-frequency, and high-temperature devices, due to its high breakdown electrical field, high saturation electron velocity, and high thermal conductivity.[1] These valuable properties for power applications largely depend on the quality of the metal/SiC contact. The formation of reliable Schottky and Ohmic contacts is necessary for power devices.[2–4]

In fact, the fabrication of Schottky and Ohmic contacts on SiC may be achieved by using different metals such as Ti,[5] Ni,[6] W,[7] Pt,[8] etc. Ni is a widely used Ohmic contact metal, which can behave as an excellent Ohmic contact after high temperature annealing.[9] Ti is often used as a Schottky metal for a low Schottky barrier height (SBH), which offers a low V_F (forward voltage drop) to reduce power dissipation.[10] However, Ti/SiC Schottky contacts often have a less than ideal forward current–voltage (I–V) characteristics,[11] which are affected by the SBH. In the process of fabrication, many treatments may affect the SBH to improve contacts on SiC. Thermal treatments are introduced by some researchers to obtain highly reproducible ideal SiC Schottky phenomena.[12] However, in spite of the 'ideal behavior' observed at room temperature, the electrical characteristics of the contacts may deviate, especially at low temperatures.[11] Besides, the value of the Richardson constant A^* is much lower than the theoretical value.[13] The above results prove the presence of an inhomogeneous Schottky barrier (SB).[13]

The inhomogeneous SB forms easily at a metal/SiC interface, possibly arising from interface states, residual processing-induced contamination, inhomogeneous doping, crystal orientation, etc.[14] Inhomogeneous SBH will lead to an undesired anomalous I–V behavior, which is often characterized by forward current at low voltage levels. Some efforts have been made to describe the anomalies in I–V characteristics of non-ideal Schottky contacts on SiC. A simple way to explain the behavior is by using a model of two different SBHs connected in parallel, as was reported by Defives *et al.*[11] However, the parallel model can lead to significant errors when the inhomogeneous SBH's length is comparable with the depletion width. A more accurate approach was presented by Tung.[15] Tung's model describes the non-ideal behavior by considering the presence of a distribution of nanometer-size 'patches' with lower barrier heights, embedded in a larger uniform area with a high barrier, and Tung's model was used to describe the non-ideal Pd/SiC,[16] Ni/SiC,[17] W/SiC[13] barriers in 4H–SiC.

Ti is widely used as the Schottky metal for SiC diodes in production. However, the reverse leakage current is a little higher for its low SBH.[10,18] In order to improve the re-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61106080 and 61275042) and the National Science and Technology Major Project of the Ministry of Science and Technology of China (Grant No. 2013ZX02305).

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verse *I–V* characteristics of Ti/SiC Schottky contacts and reduce the dependence of performance on surface preparation, thermal treatments were introduced by some researchers.[12,18] However, although the potential thermal treatment technology is applied for highly reproducible ideal SiC Schottky diodes, analyses of the degree of inhomogeneity of the SB contacts in Ti/4H–SiC with different annealing temperatures have seldom been reported in the literature.

In the present work, the electrical characterization of Ti contacts on n-type 4H–SiC after annealing at different temperatures was measured in the temperature range of 298 K–503 K. The *I–V* measurements show that the dependence of the ideality factor and SBH on measuring temperature cannot be explained by classical thermionic emission–diffusion theory. Plausible explanations were analyzed by Tung's model, which explains the inhomogeneous barrier. Furthermore, the degree of inhomogeneity of the SB was correlated with the effect of thermal treatment, and the degrees of inhomogeneity of Ti SB contacts on 4H–SiC after different thermal treatments were analyzed by the 'T_0 anomaly' of Tung's model.

2. Experiment

The Schottky diodes were fabricated on 4H–SiC n-type epitaxial wafers purchased from EpiWorld International Co., Ltd. The substrate carrier concentration is $N_D = 10^{19}$ cm^{-3}; the thickness is $t_{sub} = 350$ μm; the resistivity is 0.023 Ω·cm. The epitaxial layer's carrier concentration is $N_D = 8.27 \times 10^{15}$ cm^{-3} and its thickness is 11.98 μm. Before the back Ohmic contact was formed, the SiC wafers were treated with RCA cleaning and sacrificial oxidation. The oxide layer was removed by buffered oxide etch solution, and then the back side Ohmic contact was formed by rapid thermal annealing of a 200-nm-thick Ni film at 1000 °C for 120 s in nitrogen ambience. The Schottky patterning (diameter = 120 μm) was formed by photolithography to define the electrode patterns. After rinsing in a 10% hydrofluoric acid solution for 30 s to remove the native oxides and N_2 blow-drying, the samples were immediately transferred into the vacuum chamber of an electron beam evaporator for contact metal deposition. Then, the Schottky contact patterns were formed by a metal liftoff process. A schematic plot of the Schottky diodes is shown in Fig. 1. Five samples were prepared: four Ti samples for thermal treatment and another one without thermal treatment for comparison. The Ti Schottky samples were rapid thermal annealed (RTA) at different temperatures (300 °C, 500 °C, 700 °C, and 900 °C) for 5 min in nitrogen ambience. All the samples were characterized by *I–V* with the measuring temperature range of 298 K–508 K by using an Agilent 1500B source meter unit.

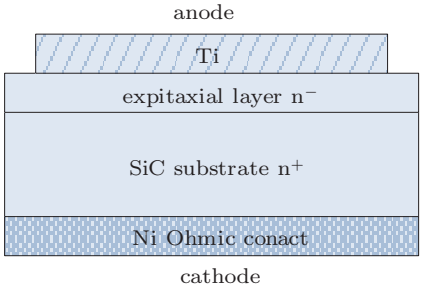


Fig. 1. (color online) Schematic cross section of 4H–SiC Schottky.

3. Results and discussion

The main electrical characteristics were deduced from *I–V* measurements made at room temperature, as summarized in Table 1. Considering the SB, ideality factor (n) and R_{on} (specific on-resistance), the samples annealed at 500-°C showed better performance. The inhomogeneous barrier of Ti/SiC annealed at 500 °C was analyzed by Tung's model in detail.

Table 1. Room temperature electrical properties of Ti/SiC Schottky diodes after rapid annealing at different temperatures

RTA temp. (5 min)	Φ_B/eV	n	R_{on}/mΩ·cm^2
As-deposited	0.56	1.26	4.04
300 °C	0.91	1.10	1.71
500 °C	1.18	1.08	1.77
700 °C	1.19	1.23	2.17
900 °C	0.77	1.46	2.13

3.1. Standard theory: Tung's model

Figure 2 shows the *I–V* characteristics of 4H–SiC Schottky rectifiers after 500-°C-temperature annealing at different temperatures ranging from 298 K to 508 K. The significant parameters governing the current transport across the Schottky contact can be determined by the *I–V* curves. The ideality factor (n) and SBH (Φ_B) can be deduced from thermionic theory (TE):[19]

$$I = I_s\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{1}$$

where I_s is the saturation current expressed by

$$I_s = SA^*T^2\exp\left(-\frac{q\Phi_B}{kT}\right), \tag{2}$$

where S is the diode area, A^* is the effective Richardson constant (146 A/cm^2·K^2 for n-type 4H–SiC[20]), T is the absolute temperature, k is the Boltzmann constant, q is the electronic charge, V is the applied voltage.

The values of n and Φ_B are determined by fitting the linear region of each *I–V* curve in Fig. 2 and are shown in Fig. 3.

As can be clearly seen from Fig. 3, Φ_B increases and n decreases with increasing temperature. The temperature dependencies of n and Φ_B indicate a deviation from the classical TE theory.[13]

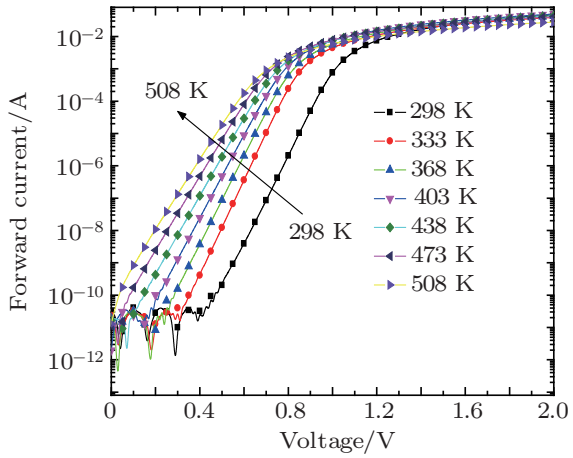


Fig. 2. (color online) I–V characteristics of the Ti/SiC Schottky contact after 500-°C thermal annealing, measured from 298 K to 503 K.

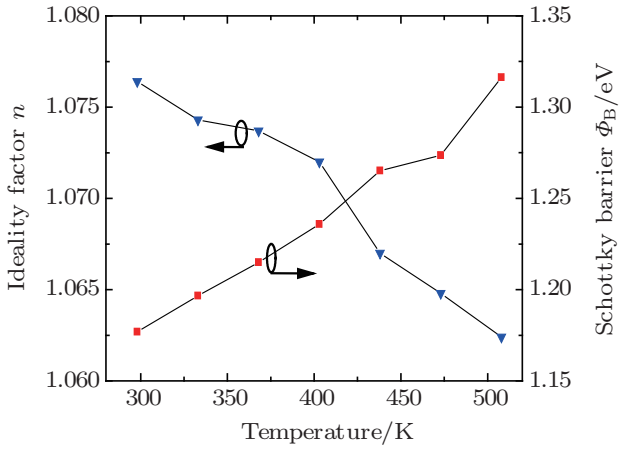


Fig. 3. (color online) Dependence of the ideality factor n and SBH Φ_B on the measurement temperature.

The barrier height and ideality factor follow a temperature behavior previously observed in [13], [21], and [22] and now referred to as the 'T_0 anomaly,' which means that the barrier is not uniform. The ideality factor can be expressed in the form of $n \approx 1 + T_0/T$.[13] Figure 4 shows the T_0 anomaly curve with an ideal Schottky contact curve as reference. The T_0 is a typical parameter of a real Schottky contact with a distributed inhomogeneous barrier.[21] The value of T_0 for the 500-°C thermal treated sample was extracted as $T_0 = 11$ K.

Figure 5 depicts the conventional Richardson's curve of $\ln(I_s/T_2)$ as a function of $(1/nkT)(\ln(I_s/T^2) = \ln(SA^*) - (q/nkT)\Phi_B^{\text{eff}})$.[13] This curve is usually used to determine the effective BH and Richardson's constant. From the slope of the linear fit to the data, the effective barrier height $\Phi_B^{\text{eff}} = 1.11$ eV, and Richardson's constant $A^* = 0.37$ A/cm^2·K^2. The extracted value of A^* is much lower than the theoretical value of 146 A/cm^2·K^2 for 4H–SiC. The smaller value of A^* indicates that the effective active region is in fact much smaller than the whole device area.[13]

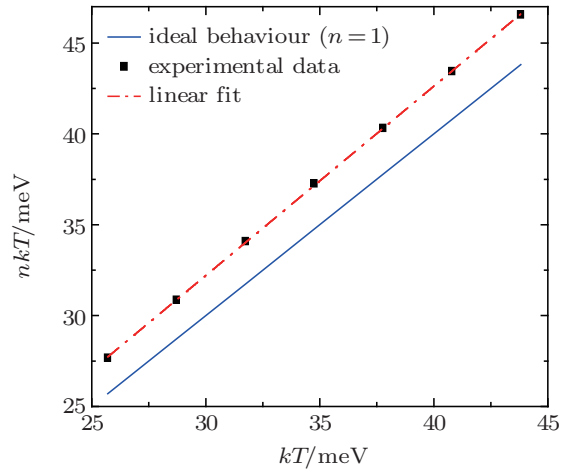


Fig. 4. (color online) Plot of nkT with kT showing the T_0 anomaly.

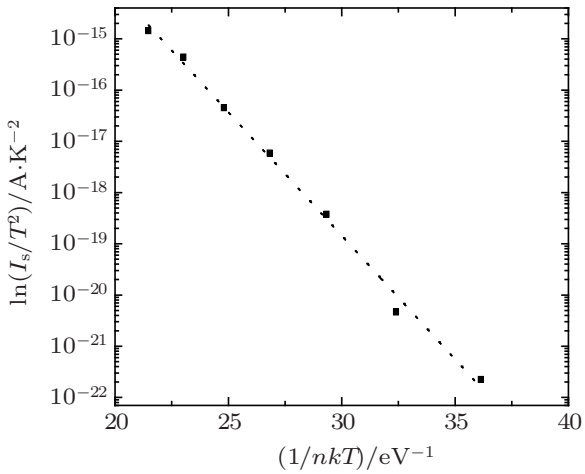


Fig. 5. Richardson's plot $\ln(I_s/T_2)$ versus $1/nkT$.

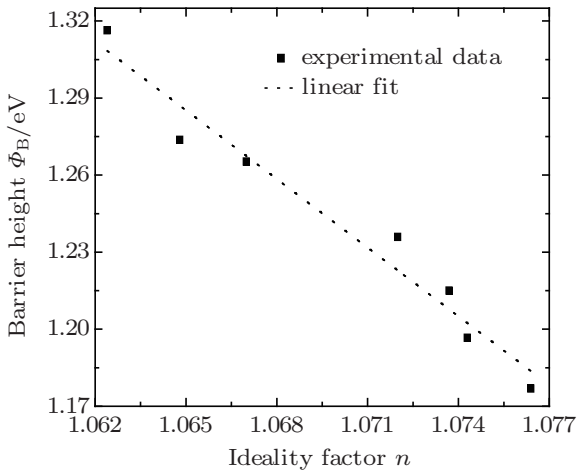


Fig. 6. SBH Φ_B versus ideality factor.

According to the procedure of Schmitsdorf *et al.*,[23] within Tung's theoretical approach to determine the value of Φ_B^0, figure 6 shows a plot of the zero-biased SBH Φ_B versus the ideality factor n. The uniform high barrier height Φ_B^0 can be found by the extrapolation of Φ_B at $n = 1$. For the 500-°C treated sample, $\Phi_B^0 = 1.86$ eV. According to Tung's model,[15] the effective SBH Φ_B^{eff} and the uniform barrier height Φ_B^0 of the metal/SiC contact are related by[24]

$$\Phi_B^{\text{eff}} = \Phi_B^0 - \gamma\left(\frac{V_{\text{bb}}}{\varepsilon_s} qN_D\right)^{1/3}, \tag{3}$$

where γ is a parameter describing the inhomogeneity of the SBH, V_{bb} is the band bending, and ε_s is the permittivity of the material. Then from Eq. (3), γ can be calculated to be 6.302×10^{-4} cm$^{2/3}$·V$^{1/3}$.

Considering the presence of the lower SBH patches embedded in the high barrier, the classical TE Eq. (1) should be rewritten as

$$I = NA_{\text{eff}}A^*T^2 \exp\left(-\frac{q\Phi_B^{\text{eff}}}{kT}\right) \times \left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{4}$$

where N is the number of patches in the contact area and A_{eff} is the area of a single patch of the lower SBH. The whole contact area A is replaced with the product of $N \cdot A_{\text{eff}}$, which represents the total area of a contact made up of low SBH. The effective area of the low SBH can be expressed as[13]

$$A_{\text{eff}} = \frac{4\pi\gamma kT}{9q}\left(\frac{\varepsilon_s}{qN_DV_{\text{bb}}}\right)^{2/3}. \tag{5}$$

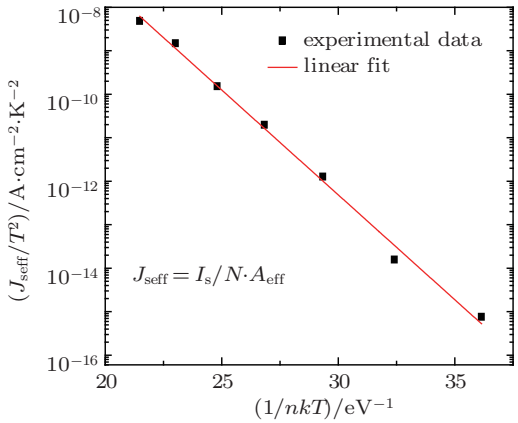


Fig. 7. (color online) "Modified" Richardson's plot $\ln(J_{\text{seff}}/T_2)$ versus $1/nkT$.

At room temperature, the value of A_{eff} was determined as $A_{\text{eff}} = 1.602 \times 10^{-11}$ cm^2. The total current flowing through the diode can be rewritten as Eq. (4). The I–V curves in Fig. 2 were all fitted with Eq. (4) using the number of patches N as a fitting parameter. The value of N was determined to be 1.8728×10^4. In order to correctly determine the value of A^*, the Richardson's plot must be modified by substituting the effective area of the patches ($N \cdot A_{\text{eff}}$) for the geometric area of the diode. The total area involved in the current transport represents only about 0.27% of the entire geometric contact area. Figure 7 shows the modified Richardson's plot. From the slope of the fitted line, the value of $\Phi_B^{\text{eff}} = 1.11$ eV is obtained, while from the intercept, the value of the Richardson constant of $A^* = 140$ A·cm^{-2}·K^2 is determined, which agrees sufficiently with the theoretical value (146 A·cm^{-2}·K^2).

3.2. Analysis of the degree of the inhomogeneous barrier height

In Tung's model, the anomaly of the electrical characterization of Ti/SiC Schottky contacts was attributed to the presence of inhomogeneities in the barrier height. The 'T_0 anomaly' and smaller Richardson's constant were analyzed by Tung's model, which assumes the contacts are formed by low-barrier patches embedded in a larger area with a uniformly high barrier. Considering the pinch-off model, the patch parameter γ is not a constant, where an inhomogeneous barrier exists, composed of a low SBH surrounded by a high SBH having a Gaussian distribution of value γ with a standard deviation σ_0. The expression of the ideality factor is given by[21]

$$n \approx 1 + \frac{q\sigma_0^2}{3kTV_{\text{bb}}^{1/3}\eta^{2/3}} \approx 1 + \frac{T_0}{T}, \tag{6}$$

$$T_0 \approx \frac{q\sigma_0^2}{3kV_{\text{bb}}^{1/3}\eta^{2/3}}, \tag{7}$$

where $\eta = \varepsilon_s/qN_D$, V_{bb} is the potential energy associated with the band bending, k is the Boltzmann constant, and T_0 and σ^2 comes from the direct proportion function. So T_0 indicates the degree of SBH inhomogeneity.[21] Moreover, the difference ($\Delta\Phi$) between the identical barrier values for the effective barrier regions (Φ_B^{eff}) and for the high uniform background barrier (Φ_B^0) can also indicate the inhomogeneity.[14]

Therefore, all the Schottky Ti/SiC samples prepared under different treatments were analyzed through the theoretical methods above: Tung's model. The different T_0 were extracted and are shown in Fig. 8. Figure 8 shows that the sample annealed at 500 °C has the lowest degree of SBH inhomogeneity, which means there are fewer small regions with low barriers through the contact.[21]

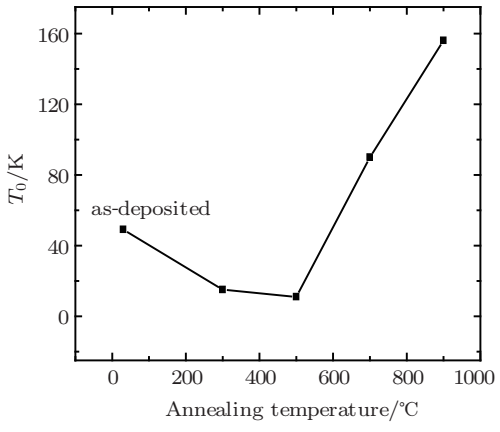


Fig. 8. T_0 anomaly versus annealing temperature.

The values of Φ_B^0 and Φ_B^{eff} and the differences ($\Delta\Phi$) for all the thermal-treated samples are shown in Fig. 9. The lowest $\Delta\Phi$ is achieved for the sample annealed at 500 °C, which means its degree of inhomogeneity is low. This result is consistent with the T_0 anomaly.

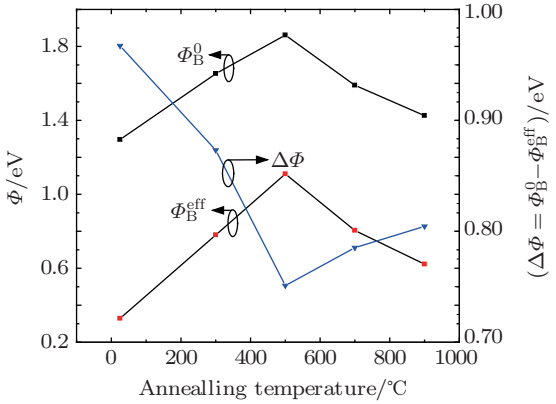


Fig. 9. (color online) Difference ($\Delta\Phi$) of Φ_B^0–Φ_B^{eff} versus annealing temperature.

The 'T_0 anomaly' shows that the degree of inhomogeneity of the barrier is at its lowest after 500-°C thermal treatment, which agrees with the $\Delta\Phi$. The above results may reflect the interface quality. The low effective SBH of as-deposited samples may be attributable to the thin residual sacrifice oxide layer that cannot be completely removed by wet etching, in which case the metal and semiconductor are separated by an interfacial oxide layer, the voltage drop across the barrier partly occurs in this layer, and the effective SBH is reduced according to Tung.[15] The samples annealed at 500 °C, which have the lowest degree of inhomogeneity of the barrier, as reflected by the T_0 anomaly and $\Delta\Phi$, explain the improvement of the interface by the thermal treatment. The reaction between Ti and SiC begins above 600 °C.[25] Though there is no reaction at the interface between the Ti and SiC at 500 °C,[26] Ti–C bonds form at the interface and the oxide layer is removed, which makes the effective barrier higher and the interface more uniform.[27] If annealed at 700 °C or 900 °C, the Ti silicide and carbide co-exist at the interface,[18,28] and they have different metallic properties, diminishing the homogeneity of the barrier.

4. Conclusion

The degree of inhomogeneity of the Ti/SiC Schottky contacts after annealing at different temperatures was investigated. All the samples were measured by *I*–*V* at elevated temperatures within the range of 298 K–508 K. The temperature dependence of the ideality factors and SBHs indicates the presence of an inhomogeneous barrier. The experimental data were analyzed in detail by using Tung's model, which allowed us to describe the contact with a homogeneous high-barrier region in which low-barrier patches are embedded. The T_0 anomaly of Tung's model shows the degree of the inhomogeneous SB, which is consistent with $\Delta\Phi$. Both of them indicate that the degree of the inhomogeneous barrier depends on the thermal annealing temperature. The 500-°C treated samples have the lowest degree of inhomogeneity of the barrier and the best electrical behavior. Both parameters indicate the degree of the inhomogeneous barrier and could be used to optimize the thermal treatment process.

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