Al/Ti/4H–SiC Schottky barrier diodes with inhomogeneous barrier heights*

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This paper investigates the current–voltage (I–V) characteristics of Al/Ti/4H–SiC Schottky barrier diodes (SBDs) in the temperature range of 77 K–500 K, which shows that Al/Ti/4H–SiC SBDs have good rectifying behaviour. An abnormal behaviour, in which the zero bias barrier height decreases while the ideality factor increases with decreasing temperature (T), has been successfully interpreted by using thermionic emission theory with Gaussian distribution of the barrier heights due to the inhomogeneous barrier height at the Al/Ti/4H–SiC interface. The effective Richardson constant $A^* = 154$ A/cm$^2 \cdot$K^2 is determined by means of a modified Richardson plot $\ln(I_0/T^2) - (q\sigma)^2/2(kT)^2$ versus q/kT, which is very close to the theoretical value 146 A/cm$^2 \cdot$K^2.

Keywords: Schottky contact, 4H–SiC, barrier height inhomogeneity, temperature

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1. Introduction

Silicon carbide (SiC) has been widely investigated and utilized as a promising material for high-temperature and high-power radio frequency (RF) applications due to its excellent electrical and physical properties.[1,2] SiC Schottky barrier diodes (SBD) are used commercially in a variety of applications, such as power conversion in motor controls and power factor correction in uninterruptible power supplies,[3,4] because of its fast switching speeds, high blocking voltages, and high temperature stability. Meanwhile, the metal/semiconductor Schottky contact is a very important cell in the fabrication of electronic devices.

One of the outstanding advantages of the 4H–SiC SBD is that it can work in high temperature conditions. Therefore, investigations of the 4H–SiC SBD current transport mechanism across a wide temperature range should help in improving the device performance and in understanding the temperature dependence of the current transport mechanism. In the present work, the current voltage characteristics of Al/Ti/4H–SiC SBDs were measured in the temperature range of 77 K–500 K. The temperature dependencies of the current transport parameters are explained based on the assumption of the existence of Gaussian distribution of the Schottky barrier around at the Al/Ti/4H–SiC interface. Also, a modified Richardson plot, $\ln(I_0/T^2) - (q\sigma)^2/2(kT)^2$ versus q/kT, is presented.

2. Experimental procedure

Commercial 4H–SiC wafers with an epitaxial layer were used to fabricate SBDs. The starting material was an n$^+$ 4H–SiC substrate with a doping concentration of 5×10^{18} cm^{-3} on which a 10-μm-thick epitaxial layer was grown, with a donor doping of 1.65×10^{15} cm^{-3}. A schematic diagram of fabricated Al/Ti/4H–SiC SBD is shown in Fig. 1. To improve the blocking characteristics, the field limiting rings (FLR) are formed by multiple aluminum implantation and the width and space of the FLR structure are 5 μm and 2 μm. The Ti/Ni (50 nm/450 nm) metals were deposited onto the wafer as an Ohmic contact. Then the wafer was annealed under N_2 ambience and 1000 °C for 120 seconds to achieve a low contact resistance. Finally, Ti/Al (200 nm/200 nm) metals were deposited onto the wafer as a Schottky contact with a diameter of 150 μm. Current–voltage (I–V) measurements were performed with an HP-4156B semiconductor parameter analyser.

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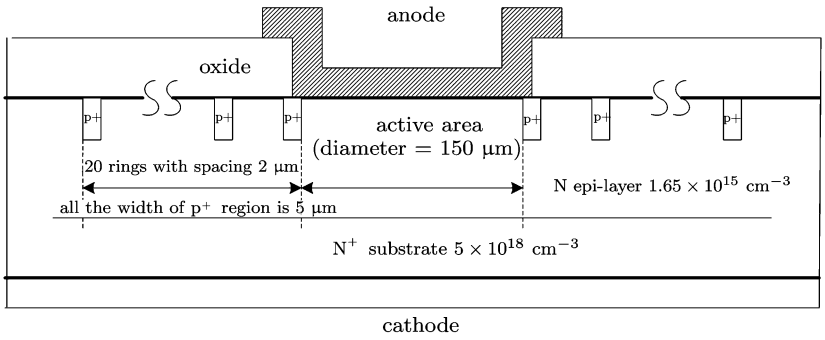


Fig. 1. Schematic diagram of fabricated Al/Ti/4H–SiC SBD.

Typical semi-logarithmic forward bias I–V characteristics of one of the Ti/Al 4H–SiC SBDs at various temperatures in the range 77 K–500 K are shown in Fig. 2. As can be seen in Fig. 2, the semi-logarithmic I–V plots are linear at low forward bias while deviation from linearity due to the influence of the series resistance and interface states at high bias range.

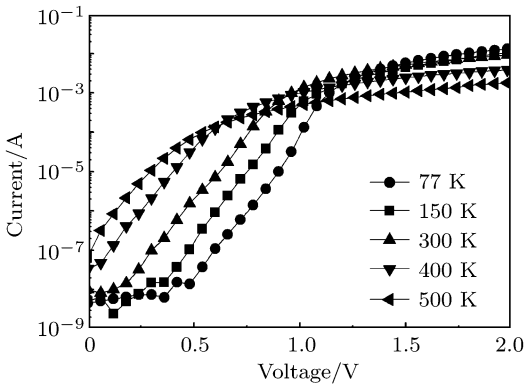


Fig. 2. Forward I–V characteristic of Al/Ti/4H–SiC SBD.

3. Results and discussion

3.1. Temperature dependence of forward I–V characteristics

The relationship between the forward voltage and the current of the SBD considering the series resistance can be expressed as follows, according to thermionic emission (TE) theory,[5]

$$I = I_0 \, \mathrm{e}^{(q(V-IR_\mathrm{s})/nkT)} \left[1 - \mathrm{e}^{(-q(V-IR_\mathrm{s})/kT)}\right], \quad (1)$$

where I_0 is the reverse saturation current obtained by extrapolating the linear intermediate voltage region part of the linear curve to zero applied voltage, and it can be written as

$$I_0 = AA^* \exp\left(\frac{q\Phi_\mathrm{b}^0}{kT}\right), \quad (2)$$

where A is the diode contact area, A^* is the effective Richardson constant, R_s is the series resistance, and T, q, k, and Φ_b^0 are the temperature, electronic charge, Boltzmann's constant, and the apparent barrier height at zero bias, respectively. The ideality factor is calculated from the slope of the liner region of the forward $\ln(I) \sim V$ plot, and from Eq. (1) it can be expressed as

$$n = \frac{q}{kT} \frac{\mathrm{d}V}{\mathrm{d}\ln(I)}. \quad (3)$$

The voltage-dependent ideality factor $n(V)$ can be derived from Eq. (1) as[6]

$$n(V) = \frac{qV}{kT\ln(I/I_0)}. \quad (4)$$

The experimental values of Φ_b^0 and n for a 4H–SiC SBD in a temperature range of 77 K–500 K can be determined from Eqs. (2) and (3), respectively. Table 1 shows the current transport parameters, such as barrier height, ideality factor, and reverse saturation current in the temperature range of 77 K–500 K. We can see that the value of n and Φ_b^0 for Ni/4H–SiC SBD ranged from 6.523 eV and 0.32 eV at 77 K to 1.232 eV and 1.302 eV at 500 K, respectively. Here the large value of the ideality factor especially at low temperature has been attributed to the particular distribution of the interface states and the presence of an interfacial layer between the metal and the semiconductor.[7]

Table 1. Current transport parameters obtained from I–V characteristics in the temperature range of 77 K–500 K.

T/K	I_0/A	n	Φ_b^0/eV
77	1.057×10^{-12}	6.253	0.32
150	2.924×10^{-11}	4.621	0.529
300	9.361×10^{-11}	2.542	0.960
400	6.270×10^{-9}	1.930	1.137
500	9.182×10^{-8}	1.232	1.302

Barrier height and ideality factor as functions of the temperature are plotted in Fig. 3, which illustrates the decrease in Schottky barrier heights and the increase in ideality factor with decreasing temperature. Such temperature dependence is an obvious disagreement from conventional TE theory. This abnormal

behaviour is also observed in other kinds of SBD, such as GaAs SBD, ZnO SBD, and Si SBD.[8−10]

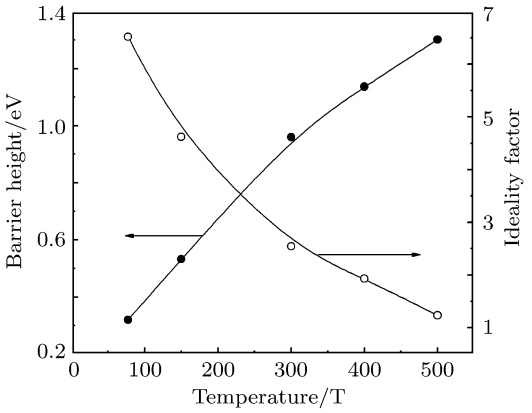


Fig. 3. Barrier height and ideality factor as a function of temperature.

To evaluate the Schottky barrier height, the activation energy plot of the reverse saturation current I_0 is usually used, which can be derived from Eq. (2),

$$\ln(I_0/T^2) = \ln(AA^*) - q\Phi_{\rm b}^0/kT. \tag{5}$$

The values of the Richardson constant can be obtained from the y-intercept of this plot. Figure 4 shows the activation energy plot of the $\ln(I_0/T^2)$ versus $1000/T$ for Al/Ti/4H–SiC SBD, which is found to be two linear regions in the measured temperature range. In the first region (77 K–300 K), the Richardson constant is obtained as 5.44×10^{-7} A/cm$^2\cdot$K^2, while in the second region (300 K–500 K), its value is 4.16×10^{-5} A/cm$^2\cdot$K^2. The Richardson constant value is much lower than the theoretical value of 146 A/cm$^2\cdot$K^2 for 4H–SiC. This deviation in Richardson plots may be due to the inhomogeneous barrier and potential fluctuations at the metal/semiconductor interface; that is, the current through the contact will flow preferably through the lower barriers.[11]

To interpret the deviation of experimental results from the conventional TE model, Tung[12] proposed a model that takes into account the possible presence of a distribution of nanometer-size "patch" with a lower barrier height embedded in a uniform high barrier background. This approach has been applied to explain a large series of abnormal experimental results on a metal/semiconductor contact and has been accepted by most people. In this case, the current through the contact may be significantly influenced by the existence of the inhomogenity of barrier heights.

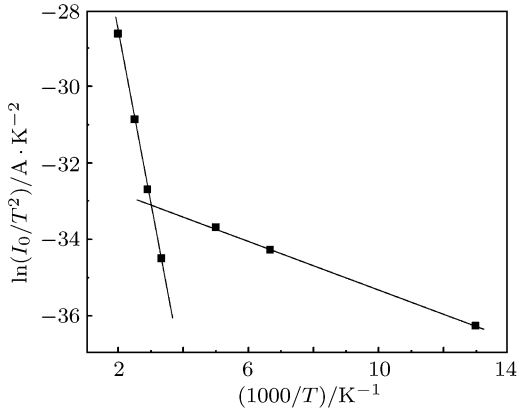


Fig. 4. Activation energy plot of the $\ln(I_0/T^2)$ versus $1000/T$ for Al/Ti/4H–SiC SBD.

According to Tung's theory, there should be a linear correlation between the $\Phi_{\rm b}^0$ and n for various temperatures. Figure 5 shows the $\Phi_{\rm b}^0$ versus n and we can see that there are two different linear regions. In the first and second regions, the homogeneous value barrier heights are determined as 1.38 eV and 0.91 eV in the case of $n = 1$, respectively. These results indicate that the current transport is controlled by different mechanisms in different temperature ranges.

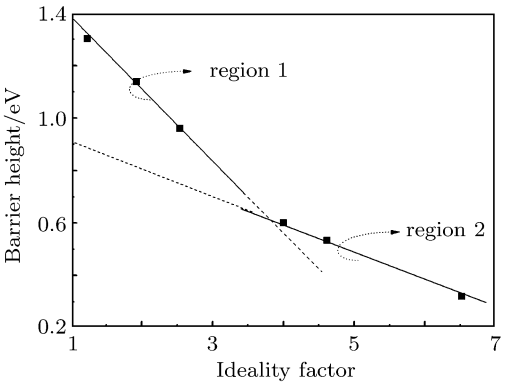


Fig. 5. Barrier height versus ideality factor.

3.2. Analysis of the inhomogeneous barrier height and modified Richardson plot

To explain the abnormal current transport behaviours previously mentioned, we adopt the TE model with a Gaussian distribution of barrier height. The Gaussian distribution of barrier height with a mean barrier height $\overline{\Phi_{\rm b}^0}$ and a standard deviation σ can be described by the following equation,[11]

$$\Phi_{\rm ap} = \overline{\Phi_{\rm b}^0} - \frac{q\sigma^2}{2kT}, \tag{6}$$

where $\Phi_{\rm ap}$ is the apparent barrier height measured experimentally. The observed variation in the ideality factor with temperature in the model is expressed

as[11]

$$(1/n_{\rm ap} - 1) = \rho_2 - \frac{q\rho_3}{2kT}, \tag{7}$$

where ρ_2 and ρ_3 are the voltage coefficient, and $n_{\rm ap}$ is the apparent ideality factor. The mean barrier height $\overline{\Phi_{\rm b}^0}$ and standard deviation σ can be determined from the plot of experimental $\Phi_{\rm ap}$ versus q/kT. Also, from the plot of $(n^{-1}-1)$ versus $q/2kT$, ρ_2 and ρ_3 can be obtained. As can be seen in Fig. 6, both the $\Phi_{\rm ap}$ versus q/kT and $(n^{-1}-1)$ versus $q/2kT$ are present. From Fig. 6(a), the mean barrier height and standard deviation can be obtained by extracting the intercepts and slopes of line at various temperatures. The $\overline{\Phi_{\rm b}^0}$ and σ are obtained as 1.48 eV and 0.036 for the first region, while 0.74 eV and 0.0069 for the second region, respectively. On the other hand, as shown in Fig. 6(b), plots of $(n^{-1}-1)$ versus $q/2kT$ also present two straight lines, and the values of ρ_2 and ρ_3 are obtained as 0.033 V and 0.12 V for the first region and 0.0025 V and 0.67 V for the second region, respectively. These results show that there are two Gaussian distributions of barrier height at the metal/4H–SiC contact.

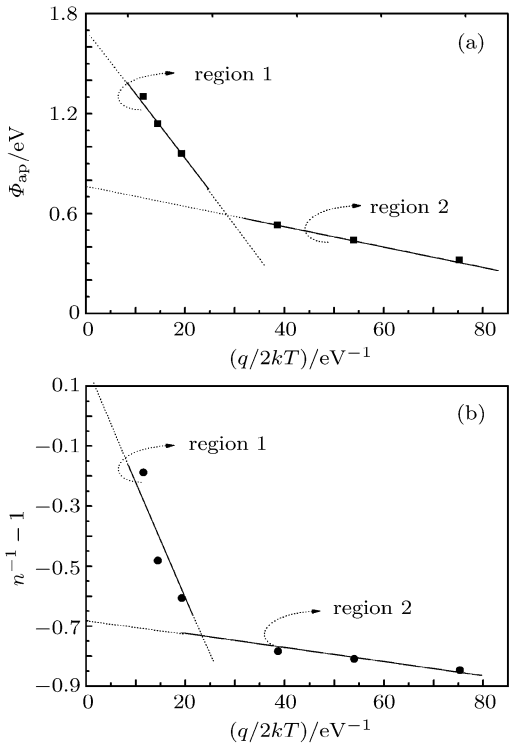


Fig. 6. The $\Phi_{\rm ap}$ versus q/kT (a) and $(n^{-1}-1)$ versus $q/2kT$ of Al/Ti/4H–SiC according to a Gaussian distribution of barriers heights.

As previously stated, the Richardson constant value determined from the conventional $\ln(I_0/T^2)$ versus $1000/T$ plot is much lower than the theoretical value of 146 A/cm$^2\cdot$K^2 for 4H–SiC. To explain this behaviour, the modified Richardson plot can be rewritten as follows,[8]

$$\ln(I_0/T^2) - \frac{1}{2}\left(\frac{q\sigma}{kT}\right)^2 = \ln(AA^*) - \frac{q\overline{\Phi_{\rm b}^0}}{kT}. \tag{8}$$

Figure 7 shows the modified Richardson plot. As can be seen in Fig. 7, the temperature dependence of $\ln(I_0/T^2) - (q\sigma)^2/2(kT)^2$ versus the q/kT plot is presented as a linear relationship in two different regions. The values of Richardson constant A^* can be extracted from the slope of the straight line as 154 A/cm$^2\cdot$K^2 for the region 1 and 89 A/cm$^2\cdot$K^2 for the region 2, which are close to the theoretical value. In particular, the Richardson constant A^* obtained from region 1 is very close to the theoretical value. These results show that the temperature dependence of current transport characteristics can be successfully interpreted by using TE theory with GD of the barrier heights due to the inhomogeneous barrier heights at the Al/Ti/4H–SiC interface.

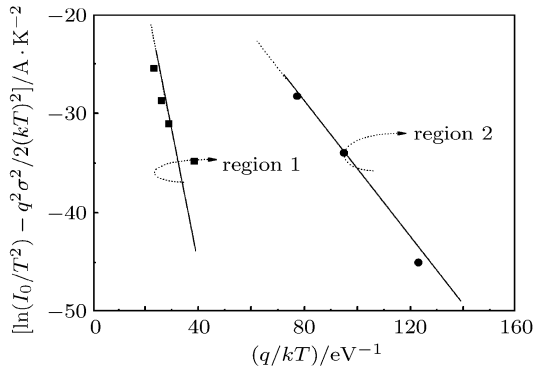


Fig. 7. The modified Richardson $\ln(I_0/T^2)$–$(q\sigma)^2/2(kT)^2$ versus q/kT plot for Ti/4H–SiC SBD according to the Gaussian distribution of barriers heights.

4. Conclusion

The temperature dependencies of current transport behaviours of the Al/Ti/4H–SiC SBD were measured in the temperature range of 77 K–500 K. The abnormal I–V characteristics with a decrease in Schottky barrier and an increase in ideality factor with decreasing temperature were observed and successfully explained by assuming GD of the barrier heights. Based on these assumptions, a modified Richardson $\ln(I_0/T^2)-(q\sigma)^2/2(kT)^2$ versus q/kT plot for Ti/4H–SiC SBD is proposed and the Richardson constant $A^* = 154$ A/cm$^2\cdot$K^2 extracted from the slope of this plot is very close to the theoretical value of 146 A/cm$^2\cdot$K^2 for 4H–SiC.

References

[1] Zhao J H, Alexandorov P and Li X 2003 *IEEE Electron Device Lett.* **24** 402

[2] Song Q W, Zhang Y M, Zhang Y M, Lü H L, Chen F P and Zheng Q L 2009 *Chin. Phys.* B **18** 5474

[3] Saxena V, Jian N S and Steckl A J 1999 *IEEE Trans. Electron Devices* **46** 456

[4] Song Q W, Zhang Y M, Zhang Y M, Zheng Q and Lü H L 2010 *Chin. Phys.* B **19** 087202

[5] Via F L, Galvagno G, Roccaforte F, Ruggiero A and Calcagno L 2005 *Appl. Phys. Lett.* **87** 142105

[6] Pakma O, Serin N, Serin T and Altindal X 2008 *J. Appl. Phys.* **104** 014501

[7] Defives D, Noblanc O, Dua C, Brylinski C, Barthula M, Fortuna V A and Meyer F 1999 *IEEE Trans. Electron Devices* **46** 449

[8] Yidiz D E, Altindal S and Kanbur H 2008 *J. Appl. Phys.* **103** 124502

[9] Ewing D J and Porter L M 2007 *J. Appl. Phys.* **101** 114514

[10] Biber M, Gullu O, Duman S and Turut A 2007 *Appl. Surf. Sci.* **253** 7246

[11] Taşçıoglu İ, Aydemir U and Altındal Ş2010 *J. Appl. Phys.* **108** 064506

[12] Tung R T 1992 *Phys. Rev.* B **45** 13509