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Temperature-dependent current–voltage characteristics of Cr/*n*-GaAs Schottky diodes

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ABSTRACT

The Cr/*n*-GaAs/In Schottky contacts have been formed using dc magnetron sputtering. The current–voltage (*I–V*) characteristics of the device have been measured by steps of 20 K in the temperature range of 60–320 K. The ideality factor *n* of the device has remained about unchanged between 1.04 and 1.10 and Schottky barrier height around 0.58–0.60 eV from 320 K down to 160 K. It can be said that the experimental *I–V* data are almost independent of temperature above 160 K. After 160 K, the *n* value increased with a decrease in temperature and become 1.99 at 60 K. The *I–V* characteristics at high temperatures have been exactly explained by the standard TE model. The nature and origin of abnormal behaviors at low temperatures have been successfully explained by the current flow through the low SBH circular patches suggested by Tung and used by some studies in literature. It has been seen that the straight line of the nT vs. T plot with a T_0 value of 14 K was parallel to that of the ideal Schottky contact. Again, a lateral homogeneous BH value of 0.62 eV was calculated from the linear relationship between the ideality factor and barrier height values. It has been seen that he $\phi(T=0)$ and BH temperature coefficient α values obtained from the flat band BH and the Norde's model plots are in close agreement with each other.

1. Introduction

GaAs is an important semiconductor used for optoelectronics, fast computers, and microwave applications. The metal-semiconductor field effect-transistor (MESFET) containing a Schottky barrier gate is one of the main components in GaAs integrated circuits [1–4]. However, the fundamental mechanisms determining the Schottky barrier height (SBH) are so far not well understood [1–7]. Sputter deposition has become a widely used technique in semiconductor technology. Good adherence of the sputter-deposited material to the substrate can be achieved for a variety of materials making the contact to the substrate more intimate than can be obtained by other commonly used deposition techniques. Dry processing techniques such as sputter etching, ion milling or reactive ion etching have proven to be very useful in obtaining a semiconductor surface free of contamination [3,5,6].

The current–voltage (*I–V*) characteristics of Schottky barrier diodes (SBDs) usually deviate from the ideal thermionic emission (TE) current model [8–15]. There are currently a vast number of reports of experimental studies of characteristic parameters such as the barrier height (BH) and ideality factor in a great variety of metal-semiconductor (MS) contacts [14–27]. Schottky diodes (SDs) with low BH have found applications in devices operating at cryogenic temperatures as infrared detectors and sensors in thermal imaging [4,20,28]. Therefore, analysis of the temperature-dependent current–voltage (*I–V*) characteristics of the Schottky barrier diodes (SBDs) gives detailed information about their conduction process or the nature of barrier formation at the MS interface. However, a complete description of the charge carrier transport through a MS contact is still a challenging problem.

In the present study, the *I–V* characteristics of Cr Schottky contacts formed by dc magnetron deposition on an *n*-GaAs substrate were measured in the temperature range of 60–320 K by steps of 20 K. At low temperatures, the temperature dependent barrier characteristics of the Cr/*n*-GaAs Schottky contacts have been interpreted by means of the thermionic emission theory of inhomogeneous Schottky contacts suggested by Tung et al. [29] and Sullivan et al. [30] who consider in their model the presence of locally non-uniform regions or patches with relatively lower or higher barriers.

2. Experimental procedure

The samples have been prepared using cleaned and polished *n*-GaAs (as received from the manufacturer) with (1 0 0) orientation and 7.3×10^{15} cm^{-3} carrier concentration. Before making contacts, the *n*-GaAs wafer was dipped in $5H_2SO_4 + H_2O_2 + H_2O$ solution for

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1.0 min to remove surface damage layer and undesirable impurities and then in H_2O + HCl solution and then followed by a rinse in de-ionized water of 18 MΩ. The wafer has been dried with high-purity nitrogen, and inserted into the deposition chamber to form ohmic contact immediately after the etching process. The indium for ohmic contact was evaporated on the back of the wafer in a vacuum-coating unit of 10^{-6} Torr. Then, the GaAs/In structure was thermally annealed to form the ohmic contact at 380 °C for 3 min in flowing N_2 in a quartz tube furnace. The Schottky contacts have been formed using dc magnetron sputtering Cr as dots with diameter of about 1.5 mm on the front surface of the *n*-GaAs. The thickness of metal coverage was determined using a quartz thickness monitor placed in close proximity to the GaAs sample. Approximately 50 nm of the Cr was performed.

The current–voltage (*I*–*V*) characteristics of the devices were measured in the temperature range of 60–320 K using a Leybold Heraeus closed-cycle helium cryostat that enables us to make measurements in the temperature range of 10–340 K, and a Keithley 487 Picoammeter/Voltage Source in dark conditions. The sample temperature was always monitored by a copper-constantan thermocouple and a Windaus MD850 electronic thermometer with sensitivity better than ±0.1 K.

3. Results and discussion

3.1. Temperature dependence of the forward bias I–V characteristics

We analyze the experimental *I*–*V* characteristics by the forward bias thermionic emission (TE) theory given as follows [2,3]

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{1}$$

where I_0 is the saturation current derived from the straight line intercept of ln*I* at *V* = 0 and is given by

$$I_0 = AA^*T^2 \exp\left(-\frac{q\Phi_{\text{eff}}}{kT}\right) \tag{2}$$

where *q* is the electron charge, *V* is the forward bias voltage, *A* is the effective diode area, *k* is the Boltzmann constant, *T* is the absolute temperature, A^* is the effective Richardson constant of 8.16 A cm^{-2} K^{-2} for n-type GaAs, ϕ_{eff} is the experimental zero bias BH (apparent barrier height) and *n* is the ideality factor. From Eq. (1), ideality factor *n* can be written as

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln I}\right) \tag{3}$$

The semilog-forward and reverse bias *I*–*V* characteristics of the Cr/*n*-GaAs SBDs are shown in the temperature range of 60–320 K by the steps of 20 K in Fig. 1. The experimental values of apparent barrier height ϕ_{eff} and *n* have been determined from intercepts and slopes of the forward bias ln*I* vs. *V* plot at each temperature using the TE theory, respectively (Fig. 2). The experimental values of ϕ_{eff} and *n* for the device range from 0.60 eV and 1.06 (at 300 K) to 0.40 eV and 1.99 (at 60 K), respectively. As can be seen from Fig. 2, the ideality factor *n* of the device has remained about unchanged between 1.04 and 1.10 from 320 K down to 160 K. That is, the experimental *I*–*V* data was fitted well over the whole bias region in the temperature range of 160–320 K. It can be said that the experimental *I*–*V* data are almost independent of the sample temperature and quite well obey the traditional thermionic emission (TE) model above 160 K. The SBH has remained about unchanged (around 0.58–0.60 eV) from 160 K to 320 K; and after 160 K, the SBH value become 0.40 eV at 60 K more decreasing with a decrease in temperature. After 160 K, the *n* value slightly increased with a decrease in temperature and become 1.99 at 60 K. The fact that the SBH decreases and *n* increases at low temperatures may be explained by current flow through the patches of lower SBH and larger ideality factor [25–30]. That is, the nature and origin of these anomalies in some studies have been successfully explained on the basis of a TE mechanism which takes into consideration the spatial barrier distribution of the BHs, due to inhomogeneities prevailing at the MS interface [29–43]. The tunneling across the barrier can be omitted due to the low doping level of the GaAs substrate [2,3,37].

The temperature dependency of the ideality factor *n* can be more understood by a plot of *nT* vs. *T*, such a plot is given for the Cr/*n*-GaAs SBD in Fig. 3, in which the dashed straight line represents the ideal behavior of a Schottky contact i.e. with *n* = 1). The temperature dependence of the ideality factor *n*(*T*) has been frequently found to have the form of *nT* = *T* + T_0, where T_0 is a constant

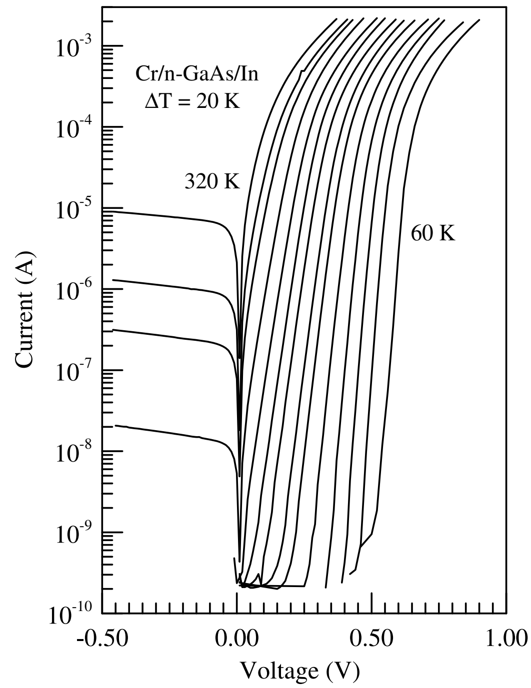

Fig. 1. Experimental forward bias current–voltage characteristics of Cr/*n*-GaAs/In Schottky contact at various temperatures.

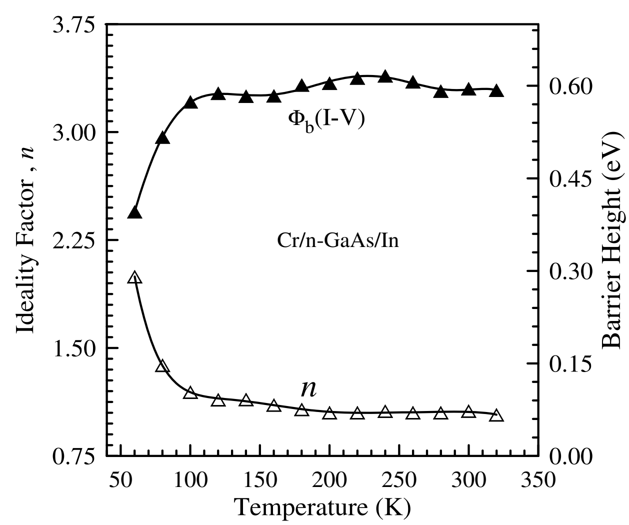

Fig. 2. Temperature dependence of the ideality factor (the open triangles) and barrier height (the filled triangles) for Cr/*n*-GaAs/In Schottky diode.

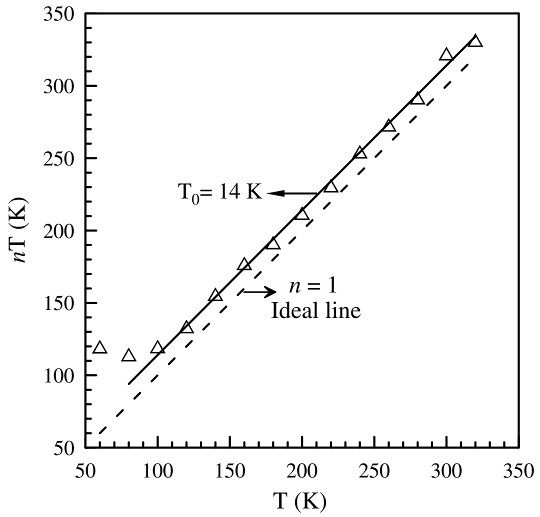

Fig. 3. Plot of nkT as a function of kT showing the T_0 anomaly from $n = 1 + (T_0/T)$. The dashed line shows the ideal behavior, $n = 1$. The open triangles are the experimental data in the temperature range of 60–320 K in Fig. 1. The full line displays the fit to the open triangles.

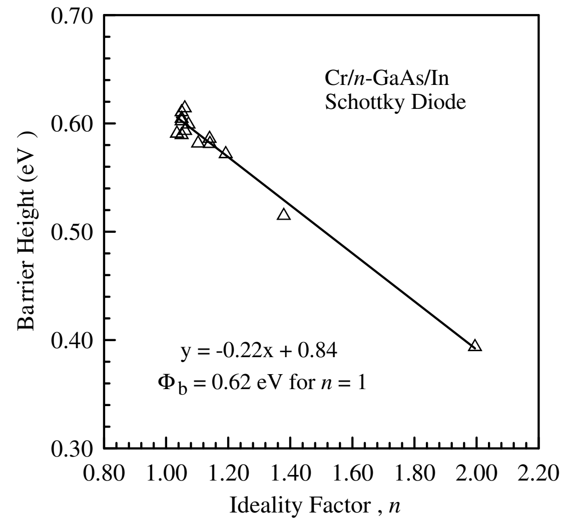

Fig. 4. The experimental zero bias apparent barrier height vs. ideality factor plot with temperature for the Cr/n-GaAs/In Schottky diode. The full line displays the fit to the open triangles.

which is independent of temperature [8–10,24–26,29,30,44]. T_0 is a measure of the temperature dependence of the ideality factor. In this behavior, the straight line fitted to the experimental values for T_0 effect should be parallel to that of the ideal Schottky contact behavior, which does not extrapolate through the origin. The straight solid line fitted to the experimental values indicated by the open triangles in Fig. 3 is parallel to that of the ideal Schottky contact behavior with a value of $T_0 = 14$ K for the device in the temperature range of 100–320 K. The straight solid line from the ideality factors close to unity in the temperature range of 100–320 K shows the situation when there is a very large region of low SBH, relative to the semiconductor depletion width, within the MS contact, as explained by Sullivan et al. [30]. Since the low SBH region is very large, almost all of the current flowing across the MS contact flows across this low SBH region. In addition, the very large region of low SBH may not be pinched-off; hence, there is no saddle point, and again the ideality factor remains close to unity [29,30]. The deviation from linearity in the nT vs. T plot below 100 K is caused by the high value of the ideality factor n since the ideality factor is characterized by the current flow through the distribution of more low SBH patches at very low temperatures [29,30]. The value of T_0 can vary between 10 and 100 K for diodes on the same slice of GaAs [2,29,30].

Furthermore, a linear relationship between the temperature-dependent barrier heights and ideality factors obtained from the experimental forward bias I–V data was observed (Fig. 4). This finding may be attributed to lateral barrier inhomogeneities in Schottky diodes [10,38–42]. The straight line was the least squares fit to our experimental data, and a lateral homogeneous BH value of 0.62 eV for the sputtered Cr/n-GaAs/In SBDs was obtained from the linear relationship in Fig. 4. As can be seen, the BH of 0.62 eV is rather close to the BH values at high temperatures. The case has been ascribed to the fact that the barrier height change decreases with increasing temperature, and thus it can be said that the barrier heights appear more uniform at higher temperatures in the Schottky diodes with the lateral inhomogeneous barrier height [29,30,43].

Moreover, an effective SBH value of 0.57 eV has been determined from the slope of the linear portion of the activation energy $\ln(I_0/T^2)$ vs. $1/kT$ plot the according to Eq. (2). This plot was indicated by the open triangles in Fig. 5. The deviation in the experimental $\ln(I_0/T^2)$ vs. $1/T$ curve at low temperatures is caused by the temperature dependence of the BH and ideality factor due to the presence of the spatially inhomogeneous BHs and potential [8–10,19–26,29,30], that is, the current through the diode will flow preferentially through the lower barriers in the potential distribution. From this plot, an effective Richardson constant of 0.76 A cm^{-2} K^{-2} is obtained. The known value of 8.16 A cm^{-2} K^{-2} for n-type GaAs is about 10.74 times larger than of 0.76 A cm^{-2} K^{-2}. Furthermore, the modified $\ln(I_0/T^2)$ vs. $1/[k(T+T_0)]$ plot (open squares) in Fig. 3 has yielded a straight line with an activation energy value of 0.66 eV in the temperature range of 100–320 K. The BH value of 0.66 eV is in close agreement with values of 0.67 eV obtained from the I–V characteristics for Cr/n-GaAs diodes in Ref. [45]. From the $\ln(I_0/T^2)$ vs. $1/[k(T+T_0)]$ plot, an effective Richardson constant of 5.10 A cm^{-2} K^{-2} is obtained, which is in close agreement with the known value of 8.16 A cm^{-2} K^{-2} for n-type GaAs.

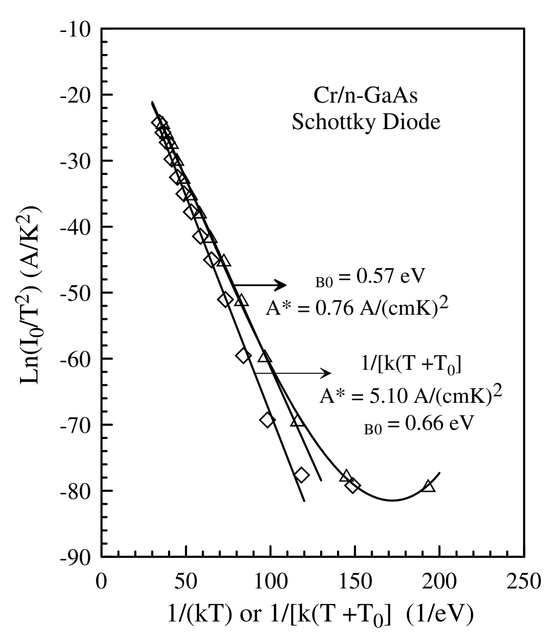

Fig. 5. Richardson plots of the $\ln(I_0/T^2)$ vs. $1/kT$ plot (the open triangles) and $\ln(I_0/T^2)$ vs. $1/[k(T+T_0)]$ plot (the open squares) for Cr/n-GaAs/In Schottky diode.

3.2. Schottky barrier inhomogeneity

The smaller value of the Richardson constant from the $\ln(I_0/T^2)$ vs. $1/(kT)$ plot in Fig. 5 indicates that the effective active area is much smaller than the device area. This anomaly and the decrease in SBH and increase in n at low temperatures cannot be exactly explained by the standard TE model. The above abnormal behaviors can rather be adequately explained using a barrier potential fluctuation model based on spatially inhomogeneous BHs at the interface by Tung [29]. It is often reasonably assumed that the I–V characteristic is dominated by the current flow through the low SBH patches because the overall current across the SBD comprises a current component arising from low barrier height regions which are interspersed within a uniform higher barrier height region [8,29,30,37]. Therefore, the current flowing through a low SBH patch will be evaluated for the case of a configuration of low circular barrier patches with the TE theory [8,29,30,37]. With a high density of patches with a broad distribution of γ-values, the current through the junction can be approximately described as [8,16,24].

$$I = NA_{\text{eff}}A^*T^2 \exp(-\beta\Phi_{\text{eff}})[\exp(\beta(V - IR_s)) - 1]. \tag{4}$$

This expression also consists of $V \leqslant 3kT/q$ values. Thus, Eq. (1) has been rewritten for the total current flowing through the diode taking into account the effective area of the diode given by NA_{eff} as previous authors have done [8,16,24]. Generally, in an inhomogeneous SBD, the expression of the current should be obtained by adding the current flowing through the low barrier patches and the current flowing through the homogeneous region. However, it is often assumed that the I–V characteristic is dominated by the current flow through the low barrier patches. In fact, as a consequence of the exponential dependence of the current on the SBHs even if the area covered by the low barrier is only few percent of the total area, the current through a contact will be mainly affected by the presence of low barrier regions [16,29,30]. If we assume a Gaussian distribution of the patch parameter γ

$$C(\gamma) = \frac{N}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\gamma^2}{\sigma^2}\right) \tag{5}$$

where γ is strength factors of the patches, σ is the standard deviation. In Eq. (5), R_s is the series resistance, N is the number of patches covering area of the diode as free parameter, $\beta = q/kT$ and A_{eff} is the effective area of a low BH patch and it can be expressed as [29]

$$A_{\text{eff}} = \frac{8\pi\sigma^2}{9}\left(\frac{\eta}{V_{\text{bo}}}\right)^{1/3}, \tag{6}$$

the product NA_{eff} represents the value of the total effective area of the patches contributing to the current transport. However, the ideality factor and effective BH for a current described by Eq. (5) in an inhomogeneous SBD are given by [29]

$$n \approx 1 + \Delta n, \quad \Delta n \approx \frac{\sigma^2 V_{\text{bo}} - V + IR_s^{-1/3}}{3kT\eta^{2/3}}, \tag{7}$$

$$\Phi_{\text{eff}} = \Phi_{\text{bo}}^{\text{hom}} - \Delta\Phi, \Delta\Phi = \frac{\sigma^2}{2kT}\left(\frac{V_{\text{bo}} - V + IR_s}{\eta}\right)^{2/3}, \tag{8}$$

respectively, where $\Phi_{\text{bo}}^{\text{hom}}$ is the homogeneous barrier height, $\eta = \varepsilon_s\varepsilon_o/qN_d$, ε_s and N_d are the dielectric constant and the dopant density of the semiconductor substrate. V_{bo} is the zero bias interface band bending of the uniform barrier outside the patch. It can obviously be seen from the equations above that the effective barrier height and ideality factor depend on the bias and temperature.

The lateral homogeneous BH value of 0.62 eV obtained from the linear relationship between the barrier heights and ideality factors (Fig. 4) and the effective BH value of 0.57 eV extracted from the Richardson's plot shown (Fig. 5) were used in Eq. (9), and it was calculated a value of 4.24×10^{-5} cm$^{2/3}$ V$^{1/3}$ for σ at 160 K. The full lines in Fig. 6 display the fits of Eq. (5) to the experimental forward bias I–V characteristics. The agreement between experimental data and fitted I–V curve in Fig. 6 is excellent i.e. the experimental I–V data are very well described by the thermionic emission theory of inhomogeneous Schottky contacts. The values of σ and N are given in the caption of the figure. As can be seen, the values of σ and N increase with increasing temperature which are in agreement with results obtained for 700 °C annealed NiSi/n-Si diode at various temperatures by Zhu et al. [37].

3.3. Flat band barrier height

The BH of a Schottky diode depends on the electric field across the contact and consequently on the applied bias voltage. It has previously been shown [46] that the flat band BH may be considered a fundamental measure of the Schottky BH that should be used when comparing experiments with theory. Under this condition, the semiconductor bands are flat, which eliminates the effect of image force lowering that would affect the I–V characteristics and removes the influence of lateral inhomogeneity. The flat band BH ϕ_{bf} can be calculated from the experimental ideality factor and zero bias BH ϕ_{bo} according to [46]

$$\Phi_{\text{bf}} = n\Phi_{\text{bo}} - (n-1)(kT/q)\ln(N_c/N_d), \tag{9}$$

where N_c is the effective density of states in the conduction band. Furthermore, the temperature dependence of the flat band BH can be expressed as

$$\Phi_{\text{bf}}(T) = \Phi_{\text{bf}}(T = 0) + \alpha T, \tag{10}$$

where $\phi_{\text{bf}}(T = 0)$ is the flat band BH extrapolated to T = 0 K, and α is its temperature coefficient. The temperature-dependent experimental N_c and N_d values were used in calculation of ϕ_{bf} values. A plot of ϕ_{bf} as a function of the temperature is shown in Fig. 7. In Fig. 7, the fitting of $\phi_{\text{bf}}(T)$ data in Eq. (10) yields ϕ_{bf} (T = 0) = 0.70 eV and α = −0.295 meV/K. The BH value of 0.70 eV is in close agreement with values of 0.72 eV obtained from the I–V characteristics for Cr/n-GaAs diodes in Ref. [47].

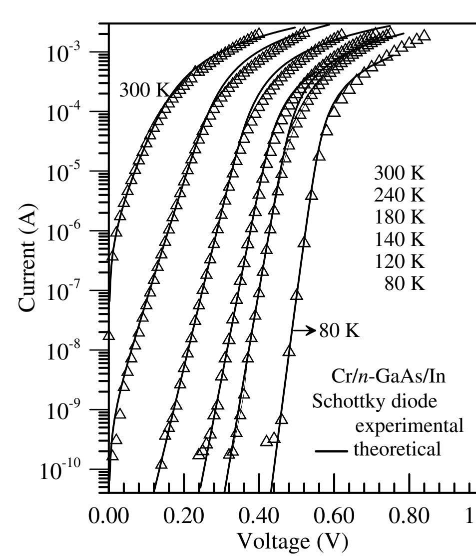

Fig. 6. The fits to the experimental forward bias I–V characteristics in Fig. 1 using Eq. (1) at 300, 240, 180 K and based on Tung's model Eq. (5) at 160, 120, 80 K. The full lines display the fits to the experimental forward bias I–V characteristics determined by the open triangles. $\sigma = 4.24 \times 10^{-5}$, 4.04×10^{-5}, 3.17×10^{-5} cm $^{2/3}$ V$^{1/3}$, $N = 6.20 \times 10^7$, 6.13×10^5, 8.15×10^7 at 140, 120, 80 K, respectively.

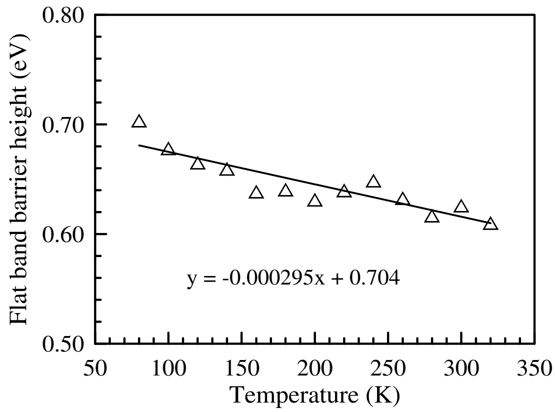

Fig. 7. Temperature dependence of the flat band barrier height for Cr/n-GaAs Schottky diode.

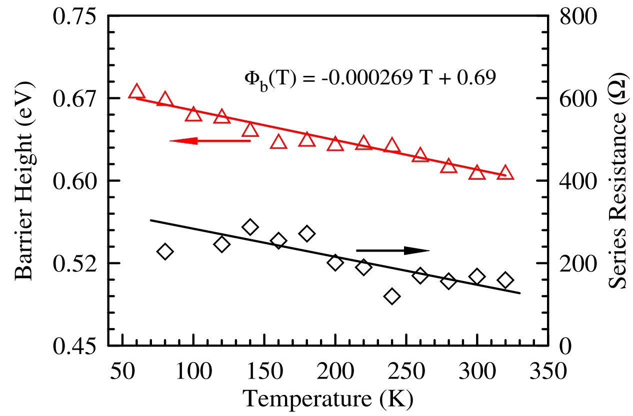

Fig. 9. Temperature dependence of the series resistance from the Norde's functions of Cr/n-GaAs Schottky diode.

3.4. Norde's function for the series resistance calculation

Norde [48] proposed a method to determine value of the series resistance. According to the thermionic emission theory, the forward bias I–V characteristics of a SBD with the series resistance can be expressed as [2]

$$I = I_0 \exp\left[\frac{q(V - IR_s)}{nkT}\right], \tag{11}$$

where R_s is the series resistance and the IR_s is the voltage drop across the series resistance of diode. Norde's function $F(V)$ has been used to obtain the values of BH and the series resistance. The $F(V)$ function is defined as [48]

$$F(V) = \frac{V}{2} - \frac{kT}{q} \ln\left(\frac{I(V)}{AA^*T^2}\right), \tag{12}$$

where $I(V)$ is current obtained from the I–V curve. A plot of $F(V)$ vs. V for the diode at different temperatures is shown in Fig. 8. From the plot of $F(V)$ vs. V, the value of the barrier height of a diode can be determined as follows [48]

$$\Phi = F(V_{\min}) + \frac{V_{\min}}{2} - \frac{kT}{q}, \tag{13}$$

where $F(V_{\min})$ is the minimum value of $F(V)$ and $V_{\min}$ is the corresponding voltage [2,46]. The BH vs. temperature plot of obtained by Norde's method for the Cr/n-GaAs SBD is given in Fig. 9 (indicated by open triangles). This value is consistent with the value obtained by the I–V method. For real contacts ($n > 1$), the series resistance R_s can be expressed as [48]

$$R_s = \frac{(2 - n)kT}{qI_{\min}} \tag{14}$$

where $I_{\min}$ is the value of the forward current at the voltage $V_{\min}$ where the function $F(V)$ exhibits a minimum. The values of series resistance from the $F(V)$–V curves as a function of temperature are given in Fig. 9 (indicated by open squares). The BH and series resistance values have increased as linear with decreasing temperature. In Fig. 7, the fitting to $\phi(T)$ data yields $\phi(T = 0) = 0.69$ eV and $\alpha = -0.269$ meV/K values which are the same as those obtained from the flat band BH vs. temperature plot. The increase of the series resistance value causes can be attributed to the freeze-out of carriers at low temperatures.

In conclusion, the apparent BH ϕ_{bo} from the current–voltage (I–V) characteristics of the Cr/n-GaAs/In Schottky contact decreases while the ideality factor n increases with a decrease in temperature due to the barrier inhomogeneity. The activation energy $\ln(I_0/T^2)$ vs. $1/kT$ plot yielded a straight line with an effective BH value of 0.57 eV. The nT vs. T plot from temperature-dependent ideality factor values obtained using the thermionic emission theory of inhomogeneous Schottky contacts have a T_0 value of 14 K for the device. The I–V characteristics at high temperatures have been exactly explained by the standard TE model. The abnormal behaviors at low temperatures have rather adequately been explained by the current flow through the low SBH circular patches suggested by Tung [29] and successfully used to elucidate the nature and origin of these anomalies in some studies [8,29,30,37]. Furthermore, a lateral homogeneous BH value of 0.62 eV for the Cr/n-GaAs SBDs was obtained from the linear relationship between the temperature-dependent ideality factor and barrier height. The BH and series resistance values have increased as linear with decreasing temperature. It has been seen that he $\phi(T = 0)$ and BH temperature coefficient α values obtained from the flat band BH vs. temperature plot and BH vs. temperature plot by the Norde's model are in close agreement with each other.

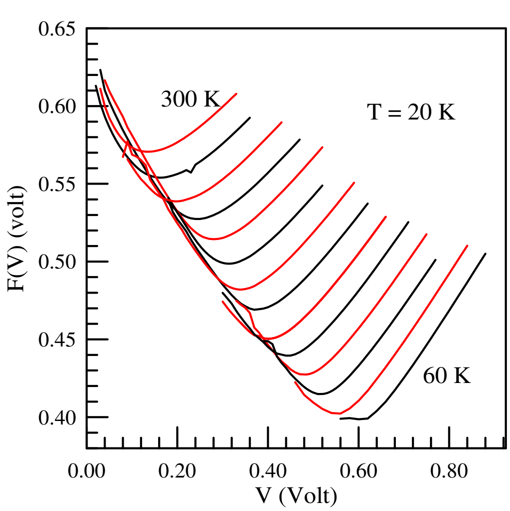

Fig. 8. $F(V)$ vs. V plot of the Cr/n-GaAs Schottky barrier diode at various temperature.

Acknowledgments

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