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Determination of barrier height temperature coefficient by Norde's method in ideal Co/n-GaAs Schottky contacts

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Abstract

We have formed the ideal Co/n-GaAs Schottky barrier diodes (SBDs) by magnetron DC sputtering. The experimental current-voltage data of the Co/n-GaAs SBD are almost independent of the sample temperature and quite well obey the thermionic emission model from 100 K to 320 K. We have showed that the temperature coefficient of the barrier height can be determined using Norde's method instead of the temperature-dependent capacitance-voltage measurements or the flat-band barrier height values because the thermionic emission current dominates in the ideal SBDs. We have obtained a barrier height temperature coefficient value of $\alpha = 0.41$ meV/K for Co/n-GaAs SBDs used in this work, which is in close agreement with values reported for the metal/n-GaAs Schottky diodes in the literature.

Key Words: Schottky barrier diode, Norde's method, GaAs, temperature coefficient of the barrier height

1. Introduction

Schottky barrier diodes (SBDs) are among the most simple MS (metal-semiconductor) contact devices, and a full understanding of the nature of their electrical characteristics is of greater interest [1–5]. GaAs is the most technologically important and the most studied compound semiconductor material. Schottky contacts on GaAs have been widely used in SBDs, metal-semiconductor field-effect transistors (MESFETs), other microwave communication devices and high-speed microelectronic applications [1–7]. Nuhoglu et al. [7] have studied the thermal stability of Co/n-GaAs SBDs annealed up to 800 °C, they [7] have obtained a Schottky barrier height (SBH) of 0.81 eV for as-deposited Co/n-GaAs at 300 K, and have deposited the Co by the evaporation on the n-GaAs to form the Schottky contact. Moreover, some researchers [8–10] have performed the room temperature I-V measurements of the Co/n-GaAs interface to determine both their SBH and ideality factor. Meskinis et al. [11] have studied the effects of low-energy nitrogen and argon ion beam irradiation at a glancing angle on chemical composition and morphology of the GaAs surface as well as electrical properties of Co/n-GaAs

Schottky contact, and obtained a SBH of 0.68 eV for the non-irradiated Co/n-GaAs Schottky contact at room temperature and observed the substantial reduction of the effective barrier height (BH) due to the irradiation.

The fact that the fundamental physical mechanisms that determine SBD parameters, such as ideality factor and the BH, are fully understood is of vital importance to all electronic and optoelectronics devices [11–17]. The temperature dependence of the current-voltage (I-V) characteristics allows us to understand different aspects of conduction mechanisms [11–17]. Analysis of the I-V characteristics of SBDs based on thermionic emission theory usually reveals an abnormal decrease in the BH and an increase in the ideality factor with a decrease in temperature [11–17]. In the present study, Co/n-GaAs Schottky barrier diodes have been prepared by DC magnetron sputtering deposition. The I-V characteristics of the produced devices have been measured in the temperature range of 60–320 K in steps of 20 K. To the best of our knowledge, the dependence of the I-V characteristics on temperature in Co/n-GaAs SBDs fabricated by magnetron sputtering or vacuum evaporation deposition technique and characterized over a wide measurement temperature range of 60–400 K have not yet been given in the literature. Diode sputtering other than vacuum evaporation technique has also become one of the frequently used techniques for the deposition of metals onto semiconductors. An advantageous feature is the good adherence of these contacts, which plays an important role in the preparation of clean surfaces. However, the investigations have shown that diode sputtering generates defects into the semiconductor substrate and create the same type of defects on Si, Ge, GaAs and InP [1, 6].

2. Experimental

The samples were prepared using cleaned and polished n-GaAs (as received from the manufacturer) with (100) orientation and 2.3×10^{15} – 3.2×10^{15} cm^{-3} carrier concentrations. Before making contacts, the n-GaAs wafer was dipped in $5H_2SO_4 + H_2O_2 + H_2O$ solution for 1.0 min to remove surface damage layer and undesirable impurities, then in a solution of H_2O+HCl, then followed by a rinse in deionized water of 18 MΩ. The wafer has been dried with high-purity nitrogen and inserted into the deposition chamber immediately after the etching process. Indium ohmic contacts were evaporated on the back of the wafer in a vacuum-coating unit pumped down to 10^{-6} Torr. The wafers were then thermally annealed at 450 °C for 3 min in flowing N_2 in a quartz tube furnace, to develop low resistance ohmic contacts. After annealing, the wafers were immediately inserted into the deposition chamber to form pure cobalt Schottky contacts of thickness approximately 500 Å. The circular Schottky contacts with a diameter of 1.5 mm on the front side of the n-GaAs wafer were formed by magnetron DC sputtering. The I-V characteristics of the devices were measured in the temperature range of 60–320 K using a Leybold Heraeus closed-cycle helium cryostat and a Keithley 487 Picoammeter/Voltage source under dark conditions. The sample temperature was always monitored by a copper-constantan (Type T) thermocouple and a Windaus MD850 electronic thermometer with sensitivity better than ± 0.1 K.

3. Results and discussion

The current through a uniform metal-semiconductor interface due to thermionic emission can be expressed as [1]

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

where I_0 is the saturation current given by

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

Here, 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_b is the zero bias apparent barrier height (BH) and n is the ideality factor. From Equation (1), ideality factor n can be written as

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

The ideality factor is introduced to take into account the deviation of the experimental I-V data from the ideal thermionic model or to include the contributions of other current transport mechanisms. It should be $n = 1$ for an ideal contact.

The experimental values of the BH and the ideality factor for the device were determined from intercept and slope of the linear portion of the forward-bias I-V plot (see Figure 1) using equations (2) and (3) at each temperature, respectively. The temperature-dependent BH and ideality factor n in the range of 60–320 K are given in Figure 2 and Table 1. However, the experimental the forward-bias $I-V$ curves are not exactly linear at 320, 300 and 280 K in Figure 1. Therefore, assuming the transport mechanism is established via the thermionic emission and attributing the deviation from linearity to series resistance; the BH and the ideality factor values were determined by Cheung's at these temperatures [18]. At the other temperatures, as seen in Figure 1, the experimental forward bias I-V data have been fitted quite well over the linear region by TE model (that is, equation (1)) in the temperature range 260–60 K, taking BH, ideality factor and the series resistance R_s as adjustable parameters.

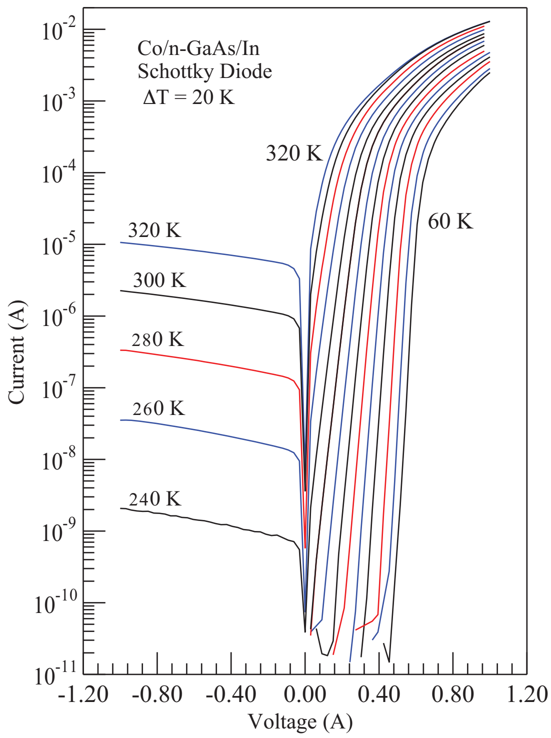

Figure 1. Current-voltage characteristics of Co/n-GaAs Schottky diode in the range of 60–320 K.

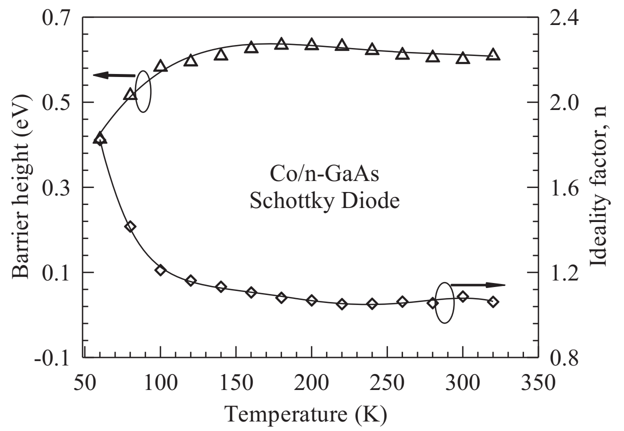

Figure 2. Temperature dependence plot of barrier height and ideality factor of the Co/n-GaAs Schottky diodes in range of 60–320 K.

Table 1. Experimental values of ideality factor n and barrier height values as a function of the measurement temperature for the Co/n-GaAs Schottky diode.

T (K)	n	Φ_b (eV)	$R_s(\Omega)$
60	1.82	0.42	59.20
80	1.42	0.52	53.15
100	1.21	0.59	46.52
120	1.16	0.60	44.30
140	1.13	0.61	42.40
160	1.11	0.63	40.64
180	1.08	0.64	39.34
200	1.07	0.64	39.11
220	1.05	0.64	38.85
240	1.05	0.63	37.70
260	1.06	0.62	36.26
280	1.06	0.61	34.10
300	1.06	0.61	31.45
320	1.06	0.61	27.78

The experimental values of BH and n for the device range from 0.42 eV and 1.82 (at 60 K) to 0.61 eV and 1.06 (at 300 and 320 K), respectively. The ideality factor is very close to unity because of the homogeneity of the interface structure. Nuhoglu et al. [7] have obtained a BH of 0.81 eV for as-deposited Co/n-GaAs at 300 K. Waldrop [8], Mclean and Williams [9] and Everaert et al. [10] have found the BH values of 0.76 eV, 0.69–0.72 eV and 0.73 eV for the Co/n-GaAs Schottky diodes at 300 K, respectively. Meskinis et al. [11] have obtained a BH value of 0.68 eV for the Co/n-GaAs Schottky contact at room temperature. These BH values are larger than the value of 0.61 eV obtained by us.

The BH value approximately remains unchanged from 100 K to 320 K while it decreases with a decrease in temperature from 100 K to 60 K. The ideality factor value approximately remains unchanged from 140 K to 320 K while it increases with a decrease in temperature from 140 K to 60 K. This change in the BH and ideality factor value at low temperatures may be explained according to new approaches based on BH inhomogeneity [11–17]. In a model developed by Tung [12], small regions, so-called "patches," with lower barrier height than the junction's main barrier was assumed to exist at the junction. The patches may result from atomic inhomogeneities such as grain boundaries, facets, defects or from high electric field at the edge of the diode. In the BH inhomogeneity model, the current mechanism was assumed to be thermionic emission over an inhomogeneous barrier. The area of these patches might be much smaller than the total area of the diode. Thus, it may be assumed that the junction's interface contains small local regions with BH of 0.42 eV at 60 K and 0.52 eV at 80 K through which charge carriers can flow. Furthermore, Anilturk and Turan have suggested the current flow through these small regions may be also assumed to be due to the tunneling type [13, 14]. Therefore, we can say that at high temperatures the current is dominated by the thermionic emission over the main barrier because of high current density and the transport through these small regions becomes gradually important with decreasing temperature [11–17].

The curvature downward in the forward I-V plots at sufficiently large applied voltage is due to bulk series resistance of the GaAs substrate. As can be seen in references [18–22], the bulk series resistance values can be determine by

$$\frac{dV}{d(\ln I)} = IR_s + n\frac{kT}{q}. \tag{4}$$

Equation (4) was derived from equation (1), this expression should give a straight line for the data of downward curvature region of the forward bias $I-V$ characteristics. Thus, the slope and y-axis intercept in the plot of $\mathrm{d}V/\mathrm{d}(\ln\ I)$ as a function of I will give R_s and nkT/q, respectively. Least-squares was used in the plots related to R_s. The plots associated with these functions are given for each temperature from 60 K to 320 K in Figure 3. The experimental series resistance value range from 27.78 Ω at 60 K to 59.20 Ω at 320 K, respectively. As can be seen from Figure 4, the series resistance value has increased with decreasing temperature in the range

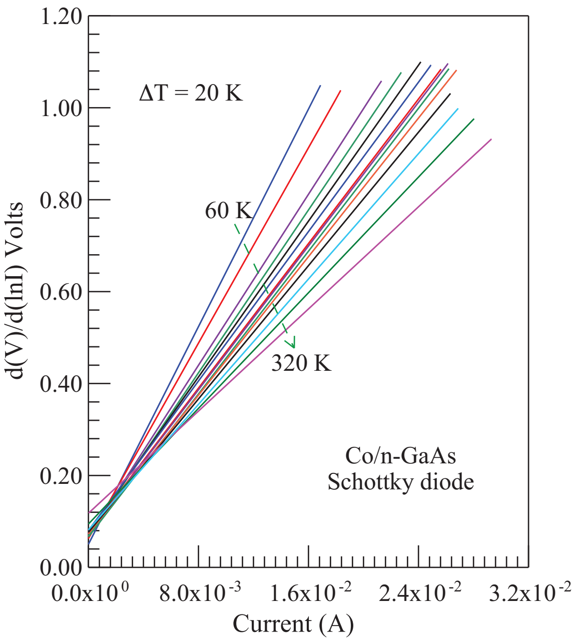

Figure 3. $\mathrm{d}(V)/\mathrm{d}(\ln\ I)$ versus current plots for determination of the series resistance of the Co/n-GaAs Schottky diode in range of 60–320 K.

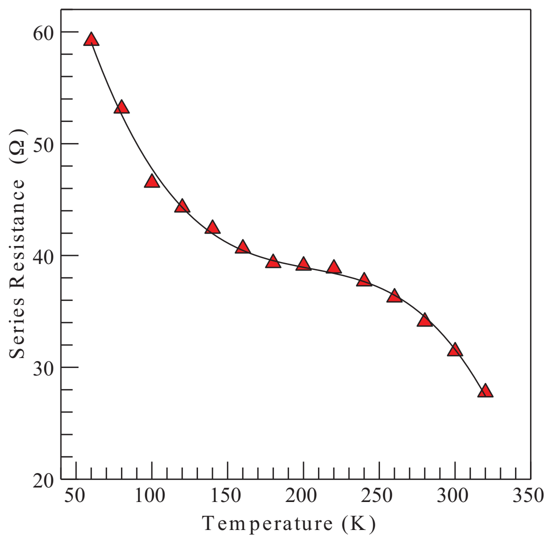

Figure 4. Temperature dependence plot of the series resistance of the Co/n-GaAs Schottky diode in range of 60-320 K.

of 60–320 K. The increase of the series resistance value with decreasing temperature can be attributed to the freeze-out of carriers at low temperatures [19, 20].

The temperature dependence of the BH and ideality factor in Schottky diodes is called the "T_0 effect" [1, 12, 23, 24]. Such a phenomenon has been observed from all types of SBDs. If a diode displays the T_0 effect, its current expression may be given by

$$I = AA^{*}T^{2}\exp\left(\frac{\Phi_b}{k(T+T_0)}\right)\exp\left(\frac{qV}{k(T+T_0)}\right)\left[1-\exp\left(-\frac{qV}{kT}\right)\right], \tag{5}$$

whereT_0 is a constant, and $(T+T_0)$ is $\underline{n}T$. The determination of value T_0 is usually accomplished by plotting the nT as a function of T and observing a straight line with a slope of unity. It was shown that the T_0 effect may be also connected either with the lateral inhomogeneity of the BH or with the role of the recombination and tunneling current components [1, 11–18, 23, 24]. Figures 5 shows a plot of nT as a function of T, reporting the temperature dependence of the ideality factor n, in which the dashed straight lines give the ideal behavior of a Schottky contact i.e., with $n= 1$. In this behavior, the straight line fitted to the experimental values for the T_0 effect should be parallel to that of the ideal Schottky contact behavior [1, 12, 23, 24]. As can be seen from Figures 5, the fitted straight line in the range of 100–320 K gives a value of 16.65 K for the T_0. The deviation from the linearity in 60–100 K can be explainable in terms of laterally SBH inhomogeneity. When the temperature is lowered, the junction current is dominated by fewer low-SBH regions with low-BHs [1, 11–18, 23, 24].

The effective BH may also be evaluated by the Richardson plot of saturation current, which is aided by re-expressing equation (2) as

$$\ln\left(\frac{I_0}{T^2}\right) = \ln\left(AA^{*}\right) - \frac{q\Phi_{b0}}{kT}. \tag{6}$$

Figure 6 shows Richardson plots of the samples, plotting the conventional $\ln(I_0/T^2)$-versus-$1/(kT)$ and the modified ($\ln(I_0/T^2)$-versus-1/[k(T $+T_0$)]. The deviation in the conventional Richardson plot may be due to the spatially inhomogeneous BHs and potential fluctuations at the interface that consist of low and high barrier areas [1, 11–18, 23, 24]. Furthermore, the current through the diode will flow preferentially through the lower barriers in the potential distribution [1, 11–18, 23, 24].

Norde [25] proposed a method to determine value of the series resistance and BH by considering equation (1) and the situation where the voltage across the diode is greater than $3kT/q$. Norde's function $F(V)$ is defined as [25]

$$F(V) = \frac{V}{\gamma} - \frac{kT}{e}\ln\left(\frac{I(V)}{AA*T^2}\right), \tag{7}$$

where $I(V)$ is current obtained from the$I-V$ curve. The plots of $F(V)$ versus V for the Co/n-GaAs SBD at different temperatures using data in Figure 1 is shown in Figure 7. From the plot of $F(V)$ versus V plot using the following equation, the value of the BH of the diode at each temperature can be determined [25]:

$$\Phi = F(V_{\min}) + \frac{V_{\min}}{2} - \frac{kT}{q}, \tag{8}$$

where $F(V_{\min})$ is the minimum value of $F(V)$ and the corresponding voltage is $V_{\min}$. The BH versus temperature plot obtained by Norde's method for the Co/n-GaAs SBD is given in Figure 8 (denoted by open triangles).

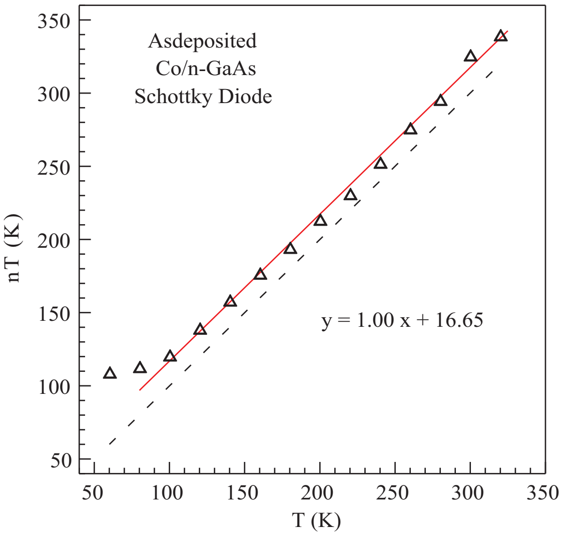

Figure 5. Plot of nT versus T showing the T_0 anomaly $n = 1 + T_0/T$ for the Co/n-GaAs Schottky Diode. The dashed straight line shows the ideal behavior given as $n = 1$.

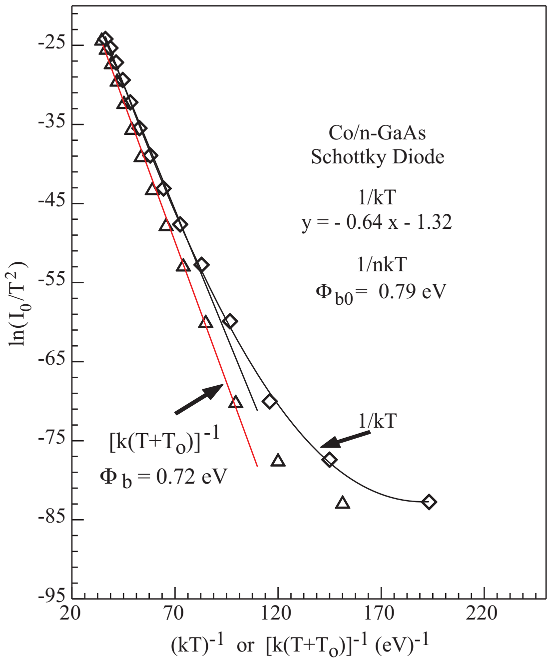

Figure 6. The experimental $\ln(I_0/T^2)$ versus $1/(kT)$ or $1/[k(T+T_0)]$ plots for the Co/n-GaAs Schottky Diode.

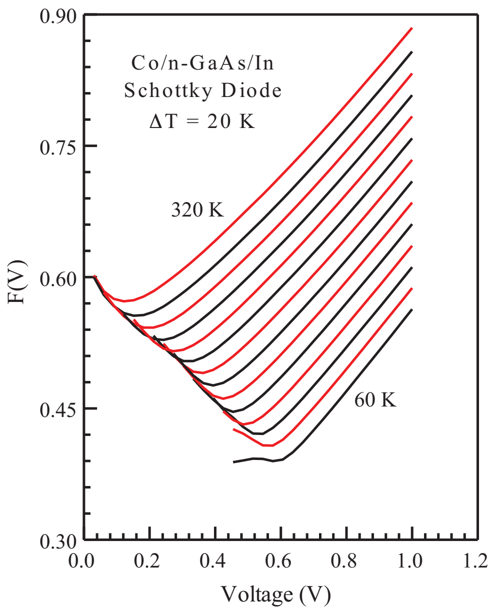

Figure 7. $F(V)$ versus V plot for the Co/n-GaAs Schottky barrier diode at various temperatures in the case where the thermionic emission dominates.

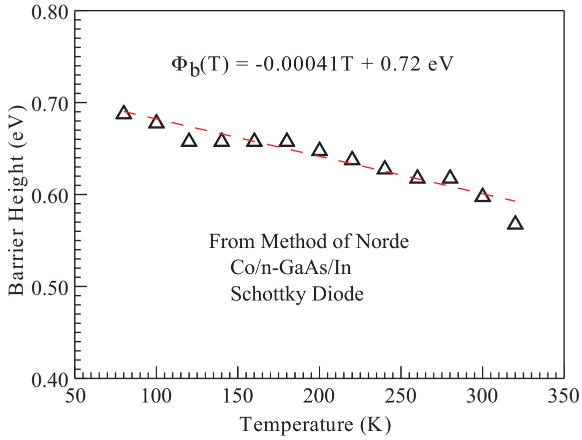

Figure 8. Temperature dependence of the barrier height determined from the Norde's functions for Co/n-GaAs Schottky diode.

As essentially indicated above, Norde's method is used to determine value of the BH in the case where thermionic emission dominates. That is, in the ideal BDs, the temperature coefficient of the BH can be determined using Norde's method [23–25]. The experimental $I - V$ data of the Co/n-GaAs SBD are almost independent of the sample temperature and quite well obey the thermionic emission (TE) model from 100 K to 320 K, as can be seen from Figures 2 and 6, and Table 1. The temperature dependence of the flat band BH can be expressed as

$$\Phi(T) = \Phi(T = 0) + \alpha T, \tag{9}$$

where $\Phi(T)$ is the experimental values determined from the plot of $F(V)$ versus V using equation (6). In the plots, $\Phi(\mathrm{T} = 0)$ is the BH extrapolated to $T = 0$ K, and α is the temperature coefficient of the BH. As seen from Figure 8, the BH values have increased as linear with a decrease in temperature. In Figure 8, the fitting to $\Phi(T)$ data according to equation (7) yields a value of Φ $(T = 0) = 0.72$ eV and the slope of straight line gives a BH temperature coefficient value of α = -0.41 meV/K. The Φ (T = 0) = 0.72 eV is the same as the effective BH value of 0.72 eV from the modified Richardson plot $\ln(I_0/T^2)$ versus $1/(kT)$ plot in Figure 5. Vurgaftman et al. [26] and Passler [27] have obtained the temperature coefficient values of -0.46 and -0.477 meV/K for the energy band gap of$n$-type GaAs, respectively. As can be seen, the value of the BH temperature coefficient is close to the value obtained for the temperature dependence of the energy band gap (within experimental errors), assuming that the variation of the BH value with temperature is entirely due to the variation in the band gap [26–33]. Ozdemir et al. [28] and Karatas and Altındal [29] have reported BH temperature coefficient values of -0.674 and -0.60 meV/K from the temperature-dependent $C^{-2} - V - T$ characteristics for Au/n-GaAs SBDs, respectively. Missous et al. [30] have obtained the values of -0.23 ± 0.03 meV/K for Au/n-GaAs and -0.32 ± 0.03 meV/K for Al/n-GaAs from the C^{-2}-V-T characteristics. Biber [31] and Hardikar [32] have reported the values of -0.778 meV/K and -0.47 ± 0.02 meV/K from the C^{-2}-V-T for Cu/n-GaAs, respectively. The variation of the BH temperature coefficient from metal to metal implies that the interface states which determine the BH depend on the metal [30]. Furthermore, it has been stated that the temperature coefficient of the BH have been correlated to the chemical nature of the contact metal or metal electronegativity [34–36].

Moreover, Göksu et al. [23] have obtained a value of α = -0.090 meV/K for Ti/n-GaAs from plotting BH against temperature using Norde's function. This negligible temperature dependence or temperature coefficient close to zero suggests that interface defects are responsible for the pinning of the Fermi level because their ionization entropy is only weakly dependent on the temperature [23, 37–39]. Thus, the dependence of BH on temperature has been ascribed to the physical mechanism of Fermi level pinning at the MS interface in some papers [23, 37–39]. That is, the Fermi level is pinned either by the metal induced gap states (MIGS) or defect states at the MS interface [23, 37–39]. When the Fermi level is pinned by MIGS, the temperature dependence of the BH is governed by the temperature dependence of the band gap. However, if the Fermi level is pinned by the interface defects, their ionization entropy would control the temperature dependence of the BH.

4. Conclusions

The results obtained for the Co/n-GaAs in the temperature range of 60–320 K indicate that magnetron DC sputtering allows realization of quality Schottky diodes. The SBH value remains almost unchanged with decreasing temperature from 320 K to 100 K. Therefore, we have attributed this behavior to the thermionic emission current to be dominant through contact in this temperature range, being for the ideal Schottky contact. We have obtained a T_0 value of 16.65 for the Co/n-GaAs Schottky diode which is very lower than the values reported for the metal/n-GaAs Schottky diodes in the literature. The case shows that the device becomes almost independent of temperature and nearly ideal in the temperature range of 100–320 K. Furthermore, Norde's function has been easily carried out to determine value of the BH temperature coefficient because the thermionic emission current dominates in the $I - V$ characteristics in the Co/n-GaAs SBD formed by us. We have obtained a BH temperature coefficient value of α = -0.41 meV/K for this Co/n-GaAs SBDs.

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