OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 4, No. 8, August 2010, p. 1229 - 1238

Electrical transport parameters of Pt/Au Schottky contacts on n-type InP in a wide temperature range

N. NANDA KUMAR REDDY, V. RAJAGOPAL REDDY*
Semiconductor Devices Lab, Department of Physics, Sri Venkateswara University, Tirupati-517 502, India

We have investigated the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of the Au/Pt/n-InP Schottky barrier diodes (SBDs) in the temperature range of 210-420 K in steps of 30 K. The electrical parameters such as ideality factor (n) and zero-bias barrier height (Φ_{bo}) are found to be strongly temperature dependent. It is observed that Φ_{bo} decreases and n and Φ_{C-V} increases with decreasing temperature. The decrease in the zero bias barrier height Φ_{bo} and an increase in the ideality factor 'n' with decrease in temperature have been explained on the basis of thermionic emission mechanism with Gaussian distribution of the barrier heights due to the BH inhomogeneities at the metal-semiconductor interface. The zero bias barrier height Φ_{bo} versus ½ kT plot shows the evidence of Gaussian distribution of the barrier heights. The values of Φ_{b0} =0.78eV and σ_0 =0.121 eV for the mean barrier height and zero bias standard deviation are obtained from this plot. The modified Richardson plot, according to inhomogeneity of BHs, has a good linearity over the temperature range. The effective Richardson constant A^* is found to be 8.09 $AK^{-2}cm^{-2}$, which is close to the theoretical value of 9.4 A $K^{-2}cm^{-2}$. The series resistance is also calculated from the forward I-V characteristics of Pt/Au SBD and found that it is strongly dependent on temperature. It is observed that the series resistance decreases with increase in temperature. As a result, it can be concluded that the temperature dependent electrical parameters for Au/Pt/n-InP SBDs can be successfully explained based on thermionic emission (TE) mechanism with Gaussian distribution of the barrier heights.

(Received July 31, 2010; accepted August 12, 2010)

Keywords: Temperature-dependent electrical properties, Pt/Au Schottky Contacts, Indium phosphide

1. Introduction

Indium phosphide, III-V compound semiconductor used in the fabrication of various electronic and optoelectronic devices have important applications in recent years. Metal film deposition on InP substrates semiconductor has received much attention in the fabrication of optoelectronics, microwave devices, and integrated circuits used in modern high speed optical communication system [1-3]. Metal semiconductor (MS) contact is one of the most widely used rectifying contacts in the electronic industry [2-6]. The performance and reliability of Schottky contacts depends on the formation of isolation layer between metal and semiconductor interface, the interface distribution between the semiconductor and insulating layer, series resistance and an inhomogeneous barrier. However, a serious limitation of InP Schottky barrier diode is the low barrier height and large leakage currents. Schottky barrier diodes with low barrier heights are also found in applications and devices operating at cryogenic temperatures as infrared detectors and thermal imaging [7,8].

Analysis of the current voltage (I-V) characteristics of the Schottky diodes obtained only at room temperature does not give detailed information about the charge transport process and about the nature of the barrier formed at the metal-semiconductor interface. The temperature dependent studies of the Schottky contact enables one to understand the charge transport process through metal-semiconductor contact and also gives a better picture of the conduction mechanism. Schottky contacts often show anomalous temperature dependent behavior of ideality factor, barrier height and series resistance. Analysis of the I-V characteristics of Schottky barrier diodes based on the thermionic emission theory (TE) usually reveals an abnormal decrease in barrier height (Φ_{bo}) and an increase in ideality factor with a decrease in temperature [9,10]. The observed current-voltage characteristics of the real Schottky barrier diode usually deviate from the ideal thermionic emission (TE) model. The strong dependence of both barrier height and ideality factor on temperature and the non-linearity of Richardson plots are the factors associated with the deviation from the TE model [11-13]. There are many mechanisms to explain these deviations, such as generation-recombination current, contamination in the interface, an intervening insulation layer, deep impurity levels, edge leakage currents, different atomic adsorbents inducing similar disruptions of the semiconductor surface lattice and the effect of image force lowering [2,3,14].

Temperature-dependent characteristics of Schottky contacts on n-type InP have been reported by many researchers [15-19]. Cetin and Ayyildiz [15] studied temperature dependence of electrical characteristics of Au/InP Schottky barrier diode. They observed that the ideality factor decreases while barrier height increases with increase of temperature. Cimilli and Saglam [16] fabricated the Au/n-InP/In Schottky barrier diodes and they reported that the experimental values of barrier height and ideality factor for the device range from 0.57eV and 1.07 (at 300 K) to 0.20 eV and 3.03 (at 70 K). Bhaskar

Reddy et al [17] studied the current-voltage-temperature (I-V-T) characteristics of Pd/Au Schottky contacts on n-InP and found that the barrier parameters vary significantly with temperature. Soylu et al [18] studied the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of the gold Schottky contacts on moderately doped n-InP Schottky barrier diodes. They found that the barrier parameters vary significantly with temperature. Recently, Cimilli et al [19] investigated the temperature dependent electrical characteristics of Ag Schottky contacts on n-InP in the temperature range of 30-320K. It was found that the decrease in the experimental barrier height calculated from I-V measurement and an increase in the ideality factor with a decrease in the temperature is due to the barrier inhomogeneities at the metal-semiconductor interface.

In the present work, the current-voltage (I-V) and capacitance-voltage(C-V) measurements of the Pt/Au Schottky contacts on n-InP have been made over the temperature range of 210 – 420 K in step of 30 K. The resultant temperature dependent barrier characteristics of the diodes have been interpreted on the basis of the existence of Gaussian distribution of the barrier heights.

2. Sample preparation and measurement condition

The Schottky barrier diodes (SBDs) were prepared using LEC grown undoped n-InP (111) wafer with carrier concentration of $4.5\times10^{15}\text{cm}^{-3}$. The samples were initially degreased with warm organic solvents such as trichloroethylene, acetone and methanol by means of ultrasonic agitation for 5 min in each stage to remove contaminants followed by rinsing in deionized water and then the samples were dried in high purity argon gas. The samples were then etched with HF (49%) and H_2O (1:10) to remove the native oxides from the substrate. Immediately after surface cleaning, high purity indium metal with a thickness of 500Å was thermally evaporated from the tungsten filament onto the rough surface of the wafer for ohmic contact. Then, the ohmic contacts were formed by thermal annealing at 350 ^{o}C for 1min in Argon atmosphere. The Schottky contacts were formed on the front face of the wafer as dots with diameter of about 0.7 mm by evaporation of Pt/Au (diode area=3.8×10^{-3} cm^2)with a thickness of 500Å each using electron beam evaporation system. All evaporation processes were carried out in a vacuum coating unit at about 7×10^{-6} mbar. The current-voltage and capacitance-voltage characteristics were measured in the temperature range 210– 420 K in steps of 30 K in the dark using temperature controller cryostat with an accuracy of ±1K. The I-V measurements were carried out by use of a Keithley Source Measure unit (Model No.2400). The capacitance-Voltage (C-V) measurements were performed using automated deep level spectrometer (SEMILAB DLS – 83D).

We analyze the experimental I-V curves according to the thermionic emission theory in which the current-voltage characteristics are given by the relation [2,20]

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

where V is the applied voltage drop across the junction barrier, q is the electronic charge, k is the Boltzmann's constant, T is the absolute temperature in Kelvin, n is the diode ideality factor and I_0 is the saturation current and is expressed [2,3] as

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

where A is the diode area, A^* is the effective Richardson's constant (9.4 $\text{Acm}^{-2}\,\text{K}^{-2}$) based on effective mass ($m^* = 0.078m_o$) of n-InP [3] and Φ_{bo} is the apparent barrier height. The values of the barrier height (Φ_{bo}), and ideality factor (n) for the device were determined from the y intercepts and slopes of the forward bias lnI versus V plot at each temperature, respectively. The barrier height (Φ_{bo}) can be obtained by rewriting Eq(2) as

$$\Phi_{b0} = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_0}\right) \tag{3}$$

The ideality factor 'n' is determined from the slope of the linear region of the plot of natural log of forward current versus forward bias voltage and is given by

$$n = \frac{q}{kT}\left(\frac{dV}{d(\ln I)}\right) \tag{4}$$

C-V measurements were also performed at a frequency of 1MHz. The C-V relationship for Schottky diode is [2,23].

$$\frac{1}{C^2} = \left(\frac{2}{\varepsilon_s q N_d A^2}\right)\left(V_{bi} - \frac{kT}{q} - V\right) \tag{5}$$

where $\in_s$ is the permittivity of the semiconductor ($\in_s = 11\in_0$), V is the applied voltage. The x-intercept of the plot of ($1/C^2$) versus V gives V_0 and it is related to the built in potential V_{bi} by the equation $V_{bi} = V_0 + kT/q$, where T is the absolute temperature. The barrier height is given by the equation $\Phi_{C-V} = V_0+V_n+kT/q$, here $V_n = (kT/q)\ln(N_c/N_d)$. The density of states in the conduction band edge is given by $N_c= 2\,(2\pi m^*kT/h^2)^{3/2}$, where $m^*=0.078m_o$ and its value is $5.7\times10^{17}\text{cm}^{-3}$ for InP at room temperature [3].

3. Results and discussion

3.1 The electrical characteristics of Schottky barrier diode as function of temperature

The semi-logarithmic reverse and forward bias current-voltage characteristics of Au/Pt/n-InP (111) Schottky barrier diode in the temperature range of 210-420 K in steps of 30 K are shown in Fig. 1. It was observed that the leakage current increased with the increase in temperature and was in the range 3.10×10^{-5}A (at 210 K) to 3.0×10^{-3}A (at 420 K) at -1V. The variation of zero bias barrier height and the ideality factor with temperature were calculated using Eq (3) and Eq (4), for Au/Pt/n-InP Schottky diode. The values of the apparent barrier height and ideality factor changed from 0.39 eV and 3.94 at 210 K to 0.59 eV and 1.62 at 420 K respectively. Fig. 2 shows that the ideality factor n exhibits an increasing trend with decreasing temperature, whereas zero bias barrier height (Φ_{b0}) decreases with decreasing temperature. The decrease in ideality factor and increase in zero bias barrier height with increasing temperature may be due to the discontinuities at the interface, which will exist even for well controlled fabrication of the sample. Many models have been evolved to explain the inhomogeneity in the barrier [2,14,21]. After Werner and Guttler [13], the potential fluctuation model was effectively used to explain the temperature dependent results of Schottky contacts rather than being predicted by other traditional models, such as image force lowering, an interfacial layer or interface states. It was explained by potential fluctuation model, which was proposed by Tung [14] to explain the inhomogeneity in the barrier height showing a larger deviation from the classical thermionic emission theory at low temperature. Due to the inhomogeneity, charge transport across the interface is no longer thermionic emission because of the presence of nano meter scale interfacial patches of small regions with low barrier heights embedded in a higher background uniform barrier [14].

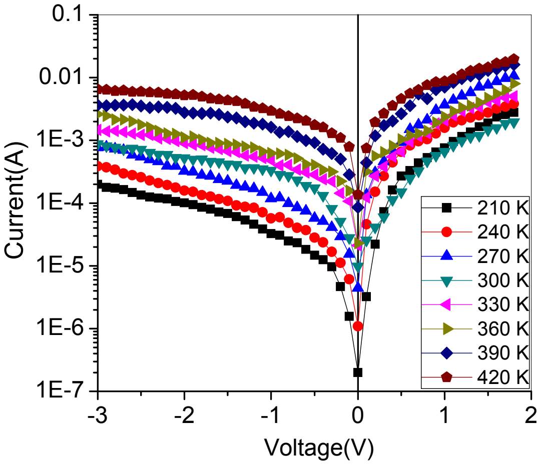

Fig. 1. Semi-logarithmic reverse and forward bias current-voltage characteristics of Au/Pt/n-InP Schottky diode in the temperature range of 210 – 420 K.

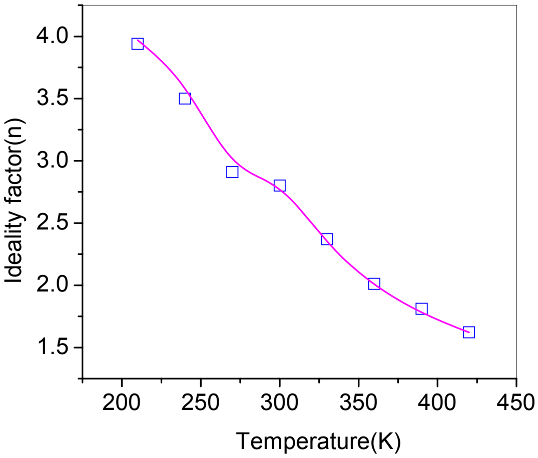

Fig. 2. Temperature dependence of the ideality factor for Au/Pt/n-InP Schottky barrier diode in the range of 210-420K. The open squares shows the experimental ideality factors and continuous curve shows the estimated value of n_{ap} using equation (12) with ρ_2 = -0.08039 V and ρ_3 = 0.02593 V.

Because current transport across the MS interface is a temperature activated process, electrons at low temperatures are able to surmount the lower barriers and therefore, current transport will be dominated by current flow through the patches of lower SBH and a larger ideality factor [13]. More and more electrons have sufficient energy to surmount the higher barrier as temperature increases, the dominant barrier height will increase with temperature and bias voltage. The higher values of the ideality factor show that there is a deviation from TE theory for current mechanism. It can be attributed to the presence of the interfacial thin native oxide layer between the metal and semiconductor [22] and / or by local inhomogenities at the Schottky contact.

The experimental reverse bias C^{-2}-V characteristics of the Au/Pt/n-InP SBD in the temperature range of 210K-420K in steps of 30K are shown in Fig. 3. The temperature dependence of the experimental carrier concentration (N_d) was calculated from the slope of reverse bias C^{-2}-V characteristics from Fig. 3 and the values of N_d varied from 1.74×10^{15} to 3.26×10^{15} cm^{-3} in the temperature range of 210K-420K. The values of Nc varied from 3.13×10^{17} to 8.87×10^{17} cm^{-3} as temperature varied between 210 K and 420 K, respectively. It was observed that carrier concentration for n-InP increased with increase in temperature. The estimated Schottky barrier height of Pt/Au Schottky contact was in the range of 0.72 eV at 210 K to 0.62 eV at 420 K respectively. It is noted that the barrier height increased with decrease in temperature.

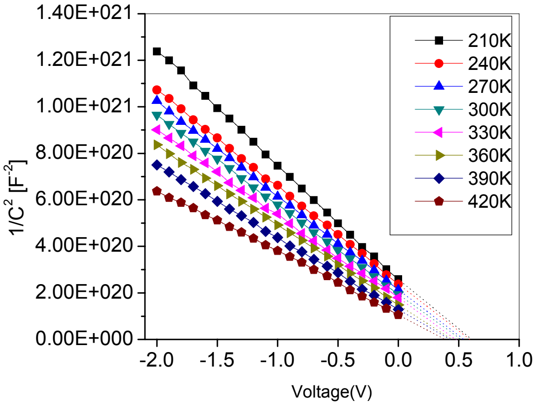

Fig. 3. The reverse bias C^{-2}-V characteristics of the Au/Pt/n-InP Schottky barrier diode in the temperature range of 210 – 420 K.

3.2 Flat-band barrier height

The barrier height, which decreases with decreasing temperature, obtained from Eq. (3) is called apparent or zero-bias barrier height. The barrier height obtained under flat-band condition is called flat-band barrier height and is considered to be the real fundamental quantity. In this case, the electric field in the semiconductor is zero and thus the semiconductor bands are flat, but the case of zero-bias barrier height is not valid. This eliminates the effect of tunneling and image force lowering that would affect the I-V characteristics and removes the influence of lateral inhomogeneity [12,24]. To find the value of Φ_{bf} , the following equation is used

$$\Phi_{bf} = n\Phi_{b0} - (n-1)\left(\frac{kT}{q}\right)\ln\left(\frac{N_c}{N_d}\right) \tag{6}$$

where N_c is the effective density of states in the conduction band and N_d the carrier concentration. The temperature dependent N_c and N_d values are used in calculating Φ_{C-V} and Φ_{bf} . Fig. 4 shows the variation of flat-band barrier height Φ_{bf} as a function of the temperature. However, Φ_{bf} is obtained to increase with decreasing temperature in a manner similar to those reported by the others [15,18,24,25]. The temperature dependence of the flat-band barrier height can be expressed as

$$\Phi_{bf}\left(T\right) = \Phi_{bf}\left(T=0\right) + \alpha T \tag{7}$$

where $\Phi_{bf}\left(T=0\right)$ and α are the flat-band barrier height extrapolated to the absolute zero and the temperature coefficient of the flat-band barrier height, respectively. The fit of eq(7) to the experimental data(filled squares) in Fig. 4 yields Φ_{bf} (T=0) = 1.68 eV and $\alpha = 2\times10^{-3}$eVK^{-1}.

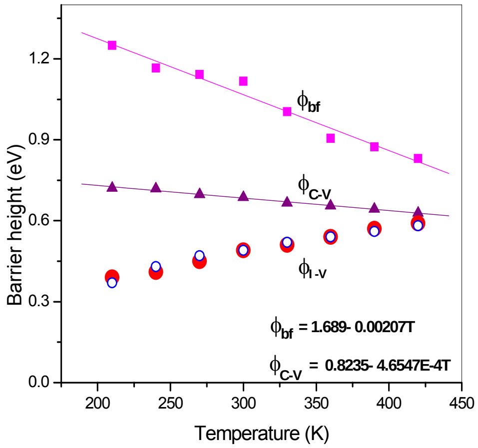

Fig. 4. Temperature dependence of the zero-bias apparent barrier height, barrier height from C-V data and flat band barrier height for Au/Pt/n-InP Schottky diode. The filled circles represent experimentally calculated barrier heights. The open circles represent estimated values of Φ_{ap} using equation (11) with

$\bar{\Phi}_{b0}$ (T=0K)= 0.78eV and =0.121eV values.

Due to the square dependence of Φ_{C-V} on 1/C, compared to the logarithmic dependence of Φ_{I-V} on the current, Φ_{C-V} is more sensitive to the experimental error of the measurement data than Φ_{IV} [26]. Moreover, it is clearly seen from the Fig. 4 that Φ_{C-V} is obtained to increase with decreasing temperature. Similar results were reported by others [15,18]. The temperature dependence of Φ_{C-V} is expressed as

$$\Phi_{C-V}\left(T\right) = \Phi_{C-V}\left(T=0\right) + \alpha T \tag{8}$$

where Φ_{C-V} (T=0K) is the barrier height extrapolated to zero temperature and α is the temperature coefficient of the barrier height. The fit of equation (8) to the experimental data (filled triangles) in Fig. 4 yields Φ_{bf} (T=0) = 0.82 eV and $\alpha = -4.6547\times10^{-4}$eVK^{-1} which is the temperature coefficient of the InP band gap [27].

3.3 Richardson plot

Fig. 5 shows a conventional activation energy $\ln(I_0/T^2)$ versus $10^3/T$ plot. According to equation (2), one obtains

$$\ln\left(\frac{I_0}{T^2}\right) = \ln\left(AA^*\right) - \frac{q\Phi_{b0}}{kT} \tag{9}$$

The Richardson constant is usually determined from the intercept of $\ln(I_0/T^2)$ versus 1000/T plot. Fig. 5 shows the plot of $\ln(I_0/T^2)$ against $10^3/T$. The plot between $\ln(I_0/T^2)$ versus 1000/T is found to be non-linear in the temperature measured. Bowing of experimental $\ln(I_0/T^2)$ versus $10^3/T$ is caused by the temperature dependence of the barrier height and ideality factor. Similar results have also been reported by several authors [14,25]. The experimental data are shown to fit asymptotically with a straight line at higher temperatures only. However for T >300 K, the experimental points lie on a straight line. An activation energy value of 0.39 eV obtained from the slope of this straight line was obtained for the device. The values of A^* obtained from the intercept of the straight line portion at the ordinate of the experimental $\ln(I_0/T^2)$ versus 1000/T plot in Fig. 5 is equal to 5.96×10^{-2} A K^{-2} cm^{-2}. The value of A^* for electrons in n-type InP is much lower than the theoretically calculated (9.4 $AK^{-2}m^{-2}$ for n-type InP) one. The deviation in the Richardson plots may be due to the spatially inhomogeneous barrier heights and potential fluctuations at the metal-semiconductor interface that consist of low and high barrier areas. That is, the current through the diode will flow preferentially through the lower barriers in the potential distribution [13, 14].

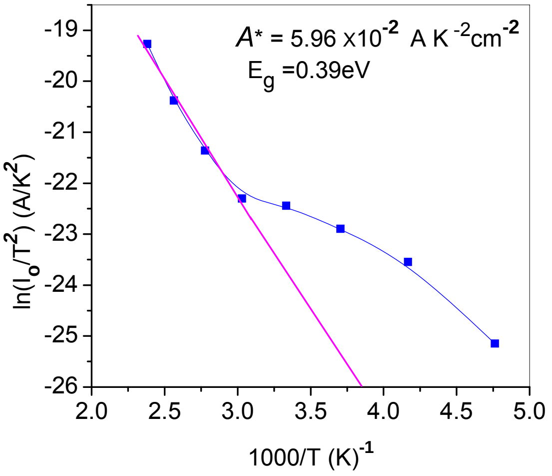

Fig. 5. Richardson plot of $\ln(I_0/T^2)$ vs. $10^3/T$ for Au/Pt/n-InP Schottky diode.

3.4 Variation of barrier height with ideality factor

The ideality factor of Schottky barrier diode with a distribution of low Schottky barrier heights may increase with a decrease in temperature [12,14]. A linear correlation between the experimental zero bias barrier height and the ideality factors could be found by Schmitsdorf et al. [28] used Tung's theoretical approach. Fig. 6 shows a plot of experimental barrier heights versus ideality factor with temperature for the Au/Pt/n-InP Schottky diode. The dotted line in Fig. 6 is the least-squares fit to the experimental data. As can be seen from Fig. 6, there is a linear relationship between the experimental effective Schottky barrier heights and the ideality factors of the Schottky contact. The extrapolation of the experimental barrier heights versus ideality factor plot to n=1 has given a homogeneous barrier height (Φ_{hom}) of approximately 0.63eV. According to the model of Tung [14], this value should represent the barrier height of the ideal homogeneous contact i.e., the highest value of the barrier height distribution in which small patches of the lower barrier is embedded. Thus, it can be said that the significant decrease of zero-bias barrier height and increase of the ideality factor especially at low temperature are possible caused by the barrier height inhomogeneities.

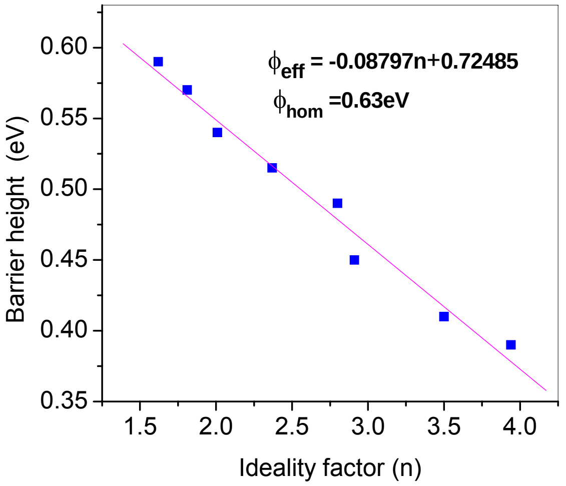

Fig. 6. The zero-bias barrier height versus ideality factor for the Au/Pt/n-InP Schottky diode at different temperatures.

3.5. Temperature dependent series resistance

As shown in Fig.1, the forward bias I-V characteristics are linear on a semi-logarithmic scale at low forward bias voltages but deviate considerably from linearity due to the effect of series resistance $R_{s,}$ the interfacial insulator layer and the interface states when the applied voltage is sufficiently large. Temperature dependence of series resistance affect on the I-V characteristics of the Au/Pt/n-InP Schottky diodes were investigated in the temperature range of 210-420 K. The resistance of the Schottky diode is the sum of the total resistance value of the resistors in series and resistance in semiconductor device in the direction of current flow. The series resistances values were evaluated from the forward bias I-V data using the method developed by Cheung [29]. The forward bias current-voltage characteristics due to thermionic emission of a Schottky contact with the series resistance can be expressed as [2,23]

$$\frac{dV}{d(\ln I)} = IR_S + n\left(\frac{kT}{q}\right) \qquad (10)$$

Fig. 7 shows the plot of dV/d (lnI) versus I as a function of temperature. Equation (10) should give a straight line for the data of downward curvature region in the forward bias I-V characteristics. Thus the slope of the plot of dV/d (lnI) versus I gives R_S as the slope and n(kT/q) as the y-axis intercept. The series resistance R_s obtained for each temperature using Eq. (10) of the I-V data increased with decrease of temperature as shown in Fig. 8. As can be seen in Fig. 8, the increase of R_S with the fall of temperature is believed to be due to factors responsible for increase in ideality factor n and lack of free carrier concentration at low temperatures [25]. The calculated series resistance of the Pt/Au Schottky contacts as a function of temperature is given in Table.1.

Table 1. Schottky barrier heights, ideality factors and series resistance of Pt/Au Schottky contact on n-type InP in the temperature range of 210-420 K.

T(K)	Barrier height			Ideality factor	Series resistance
	Φ_{bo}(eV)	Φ_{C-V}(eV)	Φ_{bF}(eV)	(n)	(Ω)
210	0.39	0.721	1.250	3.94	1098
240	0.41	0.718	1.666	3.50	769
270	0.45	0.697	1.142	2.91	570
300	0.49	0.687	1.117	2.80	512
330	0.51	0.666	1.004	2.37	491
360	0.54	0.655	0.905	2.01	332
390	0.57	0.643	0.874	1.81	189
420	0.59	0.628	0.830	1.62	105

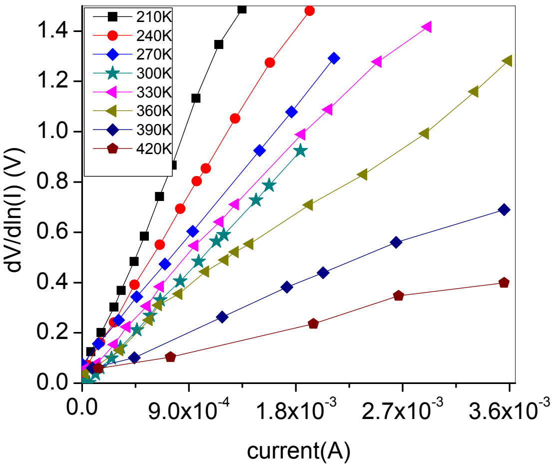

Fig. 7. Pot of dV/dln(I) versus I for Au/Pt /n-InP Schottky barrier diode.

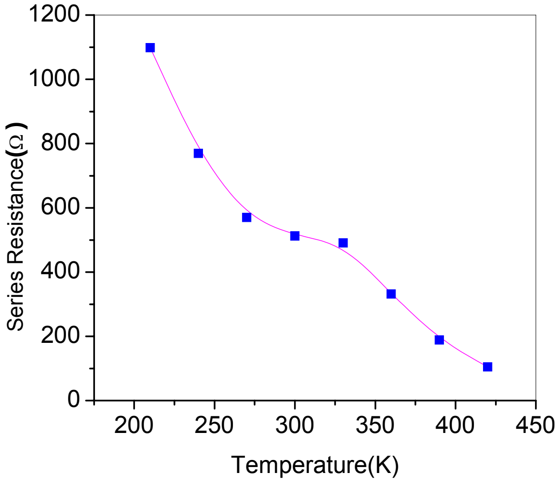

Fig. 8. Temperature dependence of series resistance of Au/Pt/n-InP Schottky barrier diode in the temperature range of 210 – 420 K.

3.6 The analysis of inhomogeneous barrier height

The discussion below will explain the commonly observed deviation from classical thermionic emission theory by a recent model based on the assumption of a spatial fluctuation of the barrier height (BH) at interface [4-6,11,13]. The decrease in the barrier height with a decrease in temperature can be explained by the lateral distribution of barrier height if the barrier height has a Gaussian distribution of barrier heights over the Schottky contact area with the mean barrier height $\bar{\Phi}_{b0}$(T=0K) and standard deviation σ_0 . The standard deviation is a measure of the barrier homogeneity. The Gaussian distribution of the BH yields the following expression for the BH [10, 11,13]

$$\Phi_{ap} = \bar{\Phi}_{b0}(\mathrm{T}=0) - \frac{q\sigma_0^2}{2kT} \qquad (11)$$

where Φ_{ap} is the apparent BH measured experimentally and σ_0 is the zero bias standard deviation of the BH distribution. The temperature dependence of σ_0 is usually small and can be neglected. The observed variation of ideality factor with temperature in the model is given by [13]

$$\left(\frac{1}{n_{ap}} - 1\right) = \rho_2 - \frac{q\rho_3}{2kT} \qquad (12)$$

where n_{ap} is apparent ideality factor (experimental data), and the coefficients ρ_2 and ρ_3 quantify the voltage deformation of the BH distribution. That is, the voltage dependencies of the mean BH and the barrier distribution widths are given by coefficients ρ_2 and ρ_3, respectively. The experimental Φ_{bo} versus 1/2kT and n_{ap} versus 1/2kT plots are shown in Fig. 9. The linearity in the apparent barrier height or ideality factor versus 1/2kT curves is in agreement with the recent model, which is related to thermionic emission over a Gaussian distribution [16]. The plot of Φ_{bo} versus 1/2kT is a straight line with the intercept on the ordinate determining the zero mean barrier height $\bar{\Phi}_{b0}$(T=0K) and the slope gives the zero bias standard deviation σ_0 . The values obtained are 0.78eV and 0.121eV for $\bar{\Phi}_{b0}$(T=0) and σ_0 respectively. Moreover, as can be seen in Fig. 4, the experimental results of Φ_{ap} fit very well with the theoretical equation (11) with $\bar{\Phi}_{b0}$(T=0)=0.78eVand σ_0 =0.121eV. The open circles in Fig. 4 indicates the data estimated with these parameters in using equation (11) and filled circles indicates the experimental barrier heights measured from I-V characteristics. The evaluated standard deviation is 15.5%of the mean barrier height. The lower value of standard deviation shows the better rectifying performance with barrier homogeneity.

The experimental ideality factor versus 1/2kT plot is a straight line as shown in Fig. 9. The values obtained for ρ_2 and ρ_3 from the intercept and the slopes of the straight line are -0.08039 V and 0.02593 V, respectively. The linear behavior of this plot reveals that the ideality factor does indeed express the voltage deformation of the Gaussian distribution of the Schottky barrier height. Furthermore, the experimental results of n_{ap} fit very well with theoretical equation (12) with ρ_2 = -0.08039 V and ρ_3 = 0.02593 V as shown in Fig. 2. The continuous solid line in Fig. 2 indicates data estimated with these parameters using equation (12) and open squares indicates experimental ideality factor values. The lower value of σ_0 corresponds to more homogeneous barrier heights. According to Cavlet et al [30], the value of σ_0 (0.121eV) is not small compared to the mean value of $\bar{\Phi}_{b0}$ (T=0)=0.78eV which indicates the greater inhomogeneities at the interface and thus potential fluctuation. The inhomogeneity and the potential fluctuation only affect low temperature current-voltage characteristics.

The conventional activation energy ln(I_0/T^2) versus 10^3/T plot has showed non-linearity at low temperatures (Fig. 5). To explain these discrepancies, according to the Gaussian distribution of the barrier height it can be rewritten by combining equations (2) and (11) as

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2\sigma_0{}^2}{2k^2T^2}\right) = \ln(AA^*) - \frac{q\bar{\Phi}_{b0}}{kT} \qquad (13)$$

Using the experimental I_0 data, a modified ln(I_0/T^2)-$\left(q^2\sigma_0{}^2/2k^2T^2\right)$ versus 1000/T plot can be obtained according to equation (13). The plot should give a straight line with the slope directly yielding the mean barrier height $\bar{\Phi}_{b0}$ (T=0) and the intercept (=lnAA*) at the ordinate, determining A* for a given diode area A. As shown in Fig. 10 modified ln $\left(I_0/T^2\right)$ – $\left(q^2\sigma_0{}^2/2k^2T^2\right)$ versus 1000/T plot yields $\bar{\Phi}_{b0}$(T=0)=0.77eV and A*= 8.09A K^{-2} cm^{-2} , respectively, without using the temperature coefficient of the barrier height. As can be seen, the value of $\bar{\Phi}_{b0}$(T=0)=0.77 eV from this plot is in agreement with the value of $\bar{\Phi}_{b0}$(T=0)=0.78eV from the plot of Φ_{ap} versus 1/T in Fig. 9.

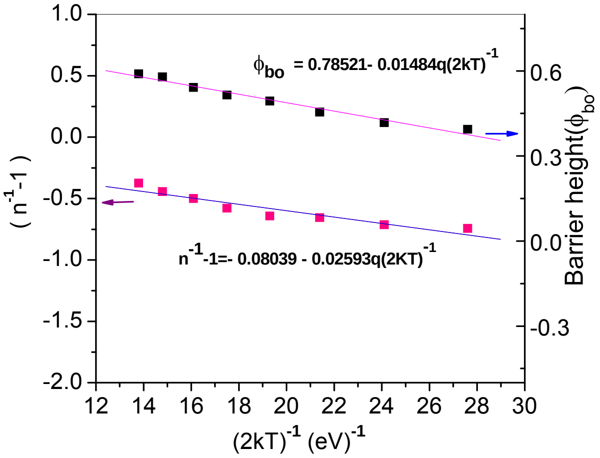

Fig. 9. The zero-bias barrier height and ideality factor versus 1/2kT plots and their linear fits for the Au/Pt/n-InP Schottky barrier diode according to Gaussian distribution of the barrier heights.

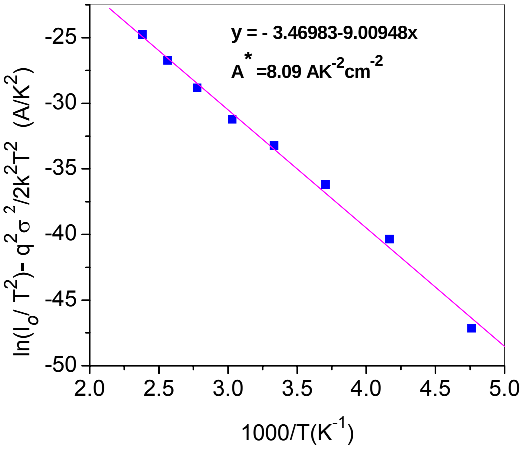

Fig. 10. Modified Richardson $\ln(I_0/T^2)-q^2\sigma_0^2/2k^2T^2$ versus1000/T plot for the Au/Pt/n-InP Schottky diode according to the Gaussian distribution of barrier heights.

It was observed that the Φ_{C-V} values were higher than the Φ_{bo} values in investigated temperature range as can be seen in Fig. 4. For the differences in BH values, some general reasons have been mentioned in the literature, such as surface contamination at the interface, deep impurity levels, an intervening insulating layer, image force lowering and edge leakage currents[14,23]. Also any damage at the interface affects the I-V behaviour because defects may act as recombination centers or as intermediate states for trap assisted tunnel currents whereas C-V measurements are less prone to such defects [20].

The discrepancy between Φ_{bo} or Φ_{I-V} and Φ_{C-V} as well as the strong temperature dependence of Φ_{bo} and n at low temperatures, can also be explained by assuming a Gaussian distribution of BHs with a mean value $\bar{\Phi}_{b0}$ and a standard deviation σ_0 [11,13,31]. The current barrier values ($\bar{\Phi}_{b0}$) are lower by a value which depends on the standard deviation σ_0, whereas the capacitance depends only on the mean band bending $\bar{\Phi}_{b0}$ and it is insensitive to the standard deviation σ_0 of the barrier height distribution which was confirmed algebraically by Werner and Guttler [13]. Hence, the capacitance barrier Φ_{C-V} is equal to the mean barrier $\bar{\Phi}_{b0}$, i.e,

$$\Phi_{C-V} = \bar{\Phi}_{b0} \tag{14}$$

Assuming a linear temperature dependence of σ_0^2 as $\sigma_0^2(T) = \sigma_0^2(T=0) + \alpha_{\sigma0}T$, the equations (11) and (14) should yield a relationship between Φ_{ap} and Φ_{C-V} as

$$\Phi_{C-V} - \Phi_{ap} = \frac{q\sigma_0^2(T=0)}{2kT} + \frac{q\alpha_{\sigma_0}}{2k} \tag{15}$$

According to equation (15) the experimental $\Phi_{C-V} - \Phi_{ap}$ versus 1/2kT plot is shown in Fig. 11. This plot must give a straight line with a slope σ_0^2 and an ordinate intercept $\alpha_{\sigma0}$ and the values are σ_0 (T=0)=0.160 eV and $\alpha_{\sigma0} = -5.29\times10^{-5}$ $(eV)^2K^{-1}$, respectively. The value of σ_0 in the investigated temperature region is in close agreement with the value of 0.121eV from the plot of Φ_{ap} versus 1/2kT given in Fig. 9. Hence, these significantly large potential fluctuations drastically affect low temperature I-V data and, in particular, they could be responsible for the curved behavior of the conventional Richardson's plot as shown in Fig. 5.

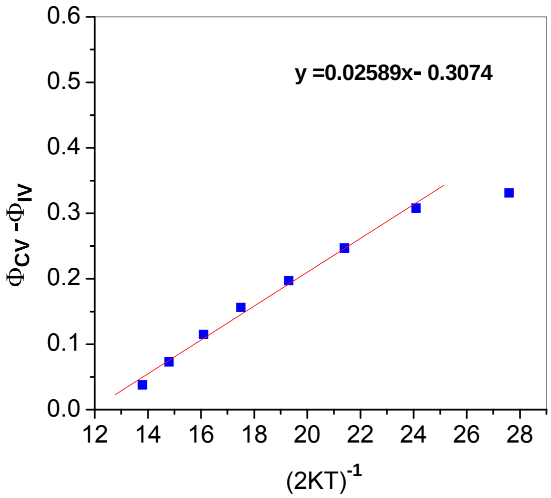

Fig. 11. Barrier height difference between values as derived from the conventional evaluation of I-V and C-V data as a function of inverse temperature.

4. Conclusions

The current-voltage and capacitance-voltage measurements of the Au/Pt/n-InP Schottky barrier diode were measured in the temperature range of 210-420 K. The calculated I-V barrier heights were in the range of 0.39-0.59eV with the ideality factor of 3.94-1.62 (210-420 K). It was found that the ideality factor (n), series resistance ($R_{s)}$ of the diode decreased while the corresponding zero-bias Schottky barrier height Φ_{bo} increased with increasing temperature. The estimated values of series resistance (Rs) of Au/Pt/n-InP are in the 1098 Ω at 210K and 105 Ω at 420K using Cheung's method. The flat band barrier height and temperature coefficient α were calculated to be $\overline{\Phi}_{bf}$ (T=0)=1.68eV and $\alpha = 2\times10^{-3}$eVK^{-1} by the I-V method. Barrier height inhomogeneiteies at the interface cause deviations in the zero-bias barrier height and the ideality factor at low temperatures, and produce extra current such that the I-V characteristics continue to remain consistent with thermionic emission process. The inhomogeneities can be described by the Gaussian distribution of barrier heights with mean barrier height $\overline{\Phi}_{b0}$ =0.78 eV and standard deviation σ_0 = 0.121eV. The experimental results of Φ_{ap} and n_{ap} fit very well with the theoretical equations related to the Gaussian distribution of Φ_{ap} and $n_{ap.}$ The laterally homogeneous SBH value of approximately 0.63eV for the Au/pt/n-InP diode was deduced from the linear relationship between the experimental barrier heights and ideality factors. The mean barrier height and the Richardson constant values were obtained as 0.77 eV and 8.09 A/cm^{2}K^2, respectively by means of the modified Richardson plot, ln(I$_0$/T^2)- $\left(q^2\sigma_0{}^2/2k^2T^2\right)$ versus 1000/T plot. Richardson constant value is in close agreement with the theoretical value of 9.4 A/cm^{2}K^2. However, the interpretation of the discrepancy between the $\overline{\Phi}_{b0}$ and Φ_{C-V} by Gaussian distribution of BHs leads to more meaningful results and thermionic emission theory. The Gaussian distribution of SBHs is thought to be responsible for the electrical behaviour of the whole investigated temperature range. In conclusion, it can be speculated from the diode parameters obtained by I-V and C-V techniques that the spatial inhomogeneities of the SBHs is an important factor and could not be ignored in the analysis of temperature dependent electrical characterization of the Schottky structures.

References

[1] H. Yan, E. Shunsuke, H. Yusuke, O. Hidenori – Chem. Lett. **36 (8)**, 986 (2007).
[2] E. H. Rhoderick, R. H. Williams – Metal-semiconductor contacts, Second ed, Oxford: Clarendon press (1988).
[3] R. H. Williams, G. Y. Robinson, in: C. W. Wilmsen (Ed.) – Physics and Chemistry of III-V compound semiconductor Interfaces, Plenum press, New York: (1985).
[4] E. Gur, S. Tuzemen, B. Kilic, C. Coskun – J . Phys. Condens. Matter. **19**, 196206 (2007).
[5] N. Rouag, L. Boussouar, S. Toumi, Z. Ouennoughi, M. A. Djouadi – Semicond. Sci. Technol. **22(4)**, 369 (2007).
[6] D. M. Kim, D. H. Kim, S. Y. Lee – Solid-State Electron. **51**, 865 (2007).
[7] S. Chand, J. Kumar – Appl. Phys. A. **65**, 497 (1996).
[8] P. G. Mc Cafferty, A. Sellai, P. Dawson, H. Elasd – Solid-State Electron. **39**, 583 (1996).
[9] R. Hackam, P. Harrop – IEEE Trans. Electron. Devices. **19**, 1231 (1972).
[10] S. Chand, J. Kumar – Semicond. Sic. Technol. **10,** 1680 (1995).
[11] Y. P. Song, R. L. Van Meirhaeghe, W. H. Laflere, F. Cardon – Solid-State Electron. **29**, 633 (1986).
[12] A. Gumus, A. Turut, N. Yalcin – J. Appl. Phys. **91,** 245 (2002).
[13] J. H. Werner, H. H. Guttler – J. Appl. Phys. **69**, 1522 (1991); J. H. Werner, H. H. Guttler – J. Appl. Phys. **73**, 1315 (1993).
[14] R. T. Tung – Phys. Rev. B. **45**, 13509 (1992); R. T. Tung – Mater. Sci. Eng. R. **35**, 1 (2001).
[15] H. Cetin, E. Ayyildiz – Semicond. Sci. Technol. **20**, 625 (2005).
[16] F. E. Cimilli, M. Saglam, H. Efeoglu, A. Turat – Physica B. **404**, 1558 (2009).
[17] M. Bhaskar Reddy, A. Ashok Kumar, V. Janardhanam, V. Rajagopal Reddy and P. Narasimha Reddy – Curr. Appl. Phy. **9**, 972 (2009).
[18] M. Soylu, B. Abay – Microelectron. Eng. **86**, 88

(2009).
[19] F. E. Cimilli, H. Efeoglu, M. Saglam, A. Turat – J. Mater. Sci: Mater. Electron. **20**, 105 (2009).
[20] D. K. Schroder – Semiconductor Material and Device Characterization, Wiley: New York (1990).
[21] C. R. Crowell, V. L. Rideout – Solid-State Electron. **12**, 89 (1969).
[22] S. Aydogan, M. Saglam, A. Turut – Appl. Surf. Sci. **43**, 250 (2005).
[23] S. M. Sze – Physics of Semiconductor Devices, second ed., John Wiley and sons, New York, (1981).
[24] S. Hardikar, M. K. Hudait, P. Modak, S. B. Krupanidhi, N. Padha – Appl. Phys. A **68**, 49 (1999).
[25] S. Chand, J. Kumar – J. Appl. Phys. **80**, 288 (1996); S. Chand, J. Kumar – Appl. phys. A. **63**, 171 (1996).
[26] S. Y. Zhu, R. L. Van Meirhaeghe, C. Detavernier, F. Cardon, G. P. Ru, X. P. Qu, B. Z. Li – Solid-State Electron. **44**, 663 (2000).
[27] Y. S. Tsay, B. Gong and S. S. Mitra – Phys. Rev. B. **6**, 2330 (1972).
[28] R. F. Schmitsdorf, T. U. Kampen, W. Monch – J. Vac. Sci. Technol. B. **15**, 1221 (1997).
[29] S. K. Cheung, N. W. Cheung – Appl. Phys. Lett. **49**, 85 (1986).
[30] E. Cavlet, R. G. Wheeler, M. A. Reed – Appl. Phys. Lett. **80**, 1761 (2002).
[31] H. K. Henisch – Semiconductor Contacts, London: Oxford University (1984).

---

* Corresponding author: reddy_vrg@rediffmail.com