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Schottky Barrier Parameters of Pd/Ti Contacts on N-Type InP Revealed from I-V-T And C-V-T Measurements

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Abstract

We report on the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of the Pd/Ti/n-InP Schottky barrier diodes (SBDs) in the temperature range 160-400 K in steps of 40 K. The barrier heights and ideality factors of Schottky contact are found in the range 0.35 eV (I-V), 0.73 eV (C-V) at 160 K and 0.63 eV (I-V), 0.61 eV (C-V) at 400 K, respectively. It is observed that the zero-bias barrier height Φ_{bo} decreases and ideality factor n increase with a decrease in temperature, this behaviour is attributed to barrier inhomogeneities by assuming Gaussian distribution at the interface. The calculated value of series resistance (R_s) from the forward I-V characteristics is decreased with an increase in temperature. The homogeneous barrier height value of approximately 0.71 eV for the Pd/Ti Schottky diode has been obtained from the linear relationship between the temperature-dependent experimentally effective barrier heights and ideality factors. The zero-bias barrier height (Φ_{bo}) versus 1/2 kT plot has been drawn to obtain evidence of a Gaussian distribution of the barrier heights and values of $\overline{\Phi}_{b0}$ = 0.80 eV and σ_0 = 114 mV for the mean barrier height and standard deviation have been obtained from the plot, respectively. The modified Richardson $\ln(I_0/T^2)-(q^2\sigma_0^2/2k^2T^2)$ versus 1000/T plot has a good linearity over the investigated temperature range and gives the mean barrier height ($\overline{\Phi}_{b0}$) and Richardson constant (A^*) values as 0.796 eV and 6.16 $Acm^{-2}K^{-2}$ respectively. The discrepancy between Schottky barrier heights obtained from I-V and C-V measurements is also interpreted.

Keywords: Schottky Barrier Parameters, I-V-T and C-V-T Measurements, Pd/Ti Schottky Contacts, N-Type InP, Gaussian Distribution

1. Introduction

Metal-semiconductor (MS) structures are important research tools in the characterization of new semiconductor materials, and at the same time, the fabrication of these structures plays a vital role in constructing some useful devices in technology [1-3]. Indium phosphide (InP) is a promising III-V compound semiconductor material for high-speed electrical and optoelectronic devices. Due to its direct bandgap, high electron mobility, high saturation velocity and breakdown voltage which are very important in electronic devices [4-5]. But, a serious limitation of InP Schottky barrier diodes is the low barrier height and large leakage currents. However, low barrier height Schottky diodes of InP seem to be a good candidate for the application of zero-bias Schottky detector diodes [5].

Most studies of Schottky barrier diodes (SBDs) formed on n-InP were limited to the determination of the Schottky barrier height (SBH) at room temperature (RT) by measuring either the current-voltage (I-V) characteristics or the capacitance-voltage (C-V) characteristics of the diodes [6-8]. Therefore, analysis of the current-voltage (I-V) characteristics of the SBDs at room temperature only does not give detailed information about their conduction process or the nature of the barrier formed at the metal-semiconductor (M-S) interface. On the other hand, the temperature dependent studies of the Schottky contacts enable one to understand different aspects of conduction mechanisms [9-11]. The observed current-voltage (I-V) characteristics of the real SBDs usually deviate from the ideal thermionic emission (TE) model. The strong dependence of both barrier height and the ideality factor on temperature, the difference in BHs obtained from different methods and the non-linearity of the Richardson's plot are the factors associated with the deviation from the TE model [9,12,13]. Explanation of the possible origin of such anomalies has been proposed, taking into account the interface state density distribution [11], quantum-mechanical tunneling [14-16], image force lowering [14] and most recently the lateral distribution of barrier height inhomogeneities [17,18]. Another way to describe the inhomogeneity is to assume a Gaussian distribution of the barrier heights over the contact area [19].

Schottky barrier diodes (SBDs) formed by depositing various metals on n- type InP have been studied over a wide temperature range [20-25]. Cetin *et al.* [20] studied the temperature dependent electrical characteristics of Au/n-InP SBDs in the temperature of 80 - 320 K. They showed that barrier heights and ideality factors varied in the range of 0.274 - 0.516 eV and 2.32 - 1.05, respectively in the measured temperature range. Bhaskar Reddy *et al.* [21] investigated the current-voltage-temperature (I-V-T) characteristics of Pd/Au/InP SBDs in the temperature range of 220 - 400 K. They reported that the barrier heights, ideality factors and series resistance were strongly temperature dependent. Soylu *et al.* [22] investigated the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of the gold Schottky contacts on moderately doped n-InP in the temperature range of 60-300 K. They found that the ideality factor n of the diode decreases while the corresponding zero-bias SBH increasing with an increase in the temperature. Ashok kumar *et al.* [23] evaluated the Schottky barrier parameters of Pd/Pt/n-InP Schottky barrier diode in the temperature range of 230 - 410 K. They found that the increase in ideality factor and decrease in barrier height with a decrease in temperature and explained such behaviour on the basis of the thermionic emission with Gaussian distribution of the barrier heights at the interface. Cimilli *et al.* [24] investigated the temperature dependent electrical characteristics of Ag Schottky contacts on n-InP in the temperature range of 30 - 320 K. They reported 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 which was due to the barrier inhomogeneities at the metal-semiconductor interface. More recently, Naik *et al.* [25] investigated the temperature dependent current-voltage (I-V) and capacitance-voltage (C-V) characteristics of the Au/Ni/n-InP SBDs in the temperature range of 210 - 420 K. They showed that the barrier parameters varied significantly with temperature.

The main aim of the present study is to fabricate Pd/Ti Schottky contacts to n-type InP and measured the current-voltage (I-V) and capacitance-voltage (C-V) characteristics in the temperature range of 160 - 400 K by steps of 40 K. In this work, titanium (Ti) is selected as a first contact layer because it has low work function and it provides the lowest forward voltage drop as well. The palladium (Pd) is used as over layer on Ti contact because it reacts with InP at low temperatures and improved contact morphology. The resultant temperature-dependent barrier characteristics of the Pd/Ti/n-InP Schottky contacts have been interpreted on the basis of the existence of Gaussian distribution of the barrier height around a mean value due to barrier height inhomogeneities prevailing at the metal-semiconductor (M-S) interface.

2. Experimental Procedure

Liquid Encapsulated Czokralski (LEC) grown undoped n-InP (111) samples with carrier concentration of 4.5×10^{15} cm^{-3} are used in the present work. Prior to metal deposition, the InP wafer is degreased for 5 min in warm organic solvents like trichloroethylene, acetone and methanol sequentially by means of ultrasonic agitation to remove contaminants followed by rinsing in deionized (DI) water and then the samples are dried in high purity N_2 gas. The cleaning procedure is followed by a 60 s dip in HF (49%) and H_2O (1:10) to remove the native oxides from the front surface of the wafer. After this etching process the wafer is immediately loaded into the deposition chamber of e-beam evaporation system. For ohmic contact, indium (In) is evaporated on to the non-polished side of the wafer with a thickness of 500 Å. Then the ohmic contacts are formed by thermal annealing at 350 ˚C for 60 s in N_2 atmosphere. Finally, Ti(200 Å)/Pd(300 Å) metals are deposited on the polished side of the InP wafer as circular dots with a diameter of 0.7 mm as Schottky contacts by electron beam evaporation system. All evaporation processes are carried out in a vacuum coating unit at about 7×10^{-6} mbar. Metal layer thickness as well as deposition rates are monitored with the help of a digital quartz crystal thickness monitor. The deposition rates are about 1.0 Ås^{-1}. The current-voltage (I-V) and capacitance-voltage (C-V) measurements are carried out by Keithley source measure unit (Model No.2400) and automated deep level spectrometer (SEMILAB DLS – 83D) in the temperature range 160 - 400 K by step of 40 K in the dark using temperature controller DLS 83D1 cryostat with a sensitivity of ±1 K.

3. Results and Discussion

3.1. Analysis of Current-Voltage-Temperature (I-V-T) Characteristics

Based on the thermionic emission theory, the current-voltage characteristics are given by the relation [1]

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

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 [1,2] as

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

where A is the diode area, A^* is the effective Richardson's constant (9.4 $A \cdot cm^{-2} \cdot K^{-2}$) based on effective mass ($m^* = 0.078\ m_o$) of n-InP [2] and Φ_{bo} is the apparent barrier height. The values of the barrier height (Φ_{bo}), and ideality factor (n) for the device are 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 Equation (2) as

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

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

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

The semi-logarithmic reverse and forward bias current-voltage characteristics of Pd/Ti/n-InP Schottky barrier diode (SBDs) in the temperature range of 160-400 K in steps of 40 K are shown in **Figure 1**. It is observed that the leakage current increase with the increase in temperature is in the range 2.44 × 10^{-7} A (at 160 K) to 1.21 × 10^{-3} A (at 400 K) at –1 V. Measurements showed that the zero bias barrier height and the ideality factor (calculated using Equations (3) and (4)) of Pd/Ti/n-InP SBDs with temperature are 0.35 eV and 3.75 at 160 K to 0.63 eV and 1.73 at 400 K respectively. It is noted that the barrier height (BH) is increased linearly from 0.35 eV to 0.63 eV with the increase in temperature from 160 K to 400 K, accompanied by a significant improvement of the ideality factor n from 3.75 to 1.73. Interestingly it is noted that the experimental value of Φ_{bo} is found to increases with increase in temperature as shown in **Figure 2**. Since current transport across the metal-semiconductor interface is controlled by temperature, electrons at low temperature pass over the lower barriers and therefore current will flow through patches of the lower SBH and results in a larger ideality factor. In other words, as the temperature increases, more and more electrons have sufficient energy to overcome the higher barrier [11,26]. **Figure 3** shows that the experimental values of n (represented by open circles) increased with a decrease in temperature. The higher values of the ideality factor (n > 1) indicate that there is a deviation from TE theory for current mechanism. Idealities greater than one can be attributed to the presence of a thick interfacial insulator layer between the metal and semiconductor [1,27].

As shown in the **Figure 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). Temperature dependence of series resistance effect on the I-V characteristics of the Pd/Ti/n-InP SBDs are investigated

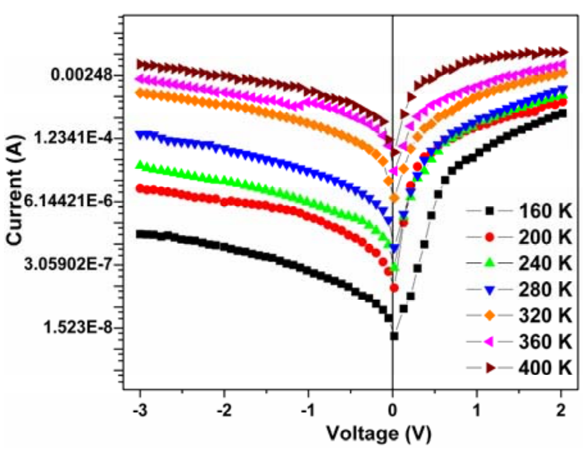

Figure 1. Semi-logarithmic reverse and forward bias current-voltage characteristics of Pd/Ti/n-InP SBD in the temperature range of 160 - 400 K.

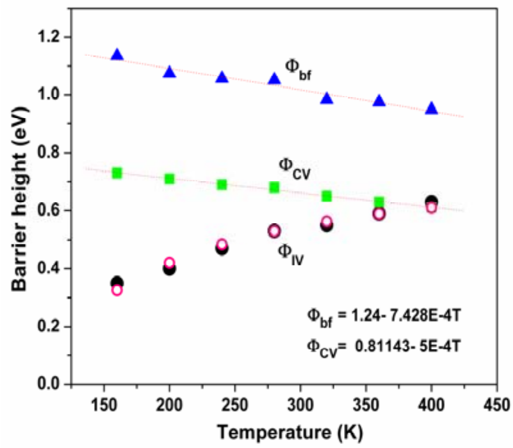

Figure 2. Temperature dependence of the zero-bias apparent barrier height, barrier height from C-V data and flat band barrier height for Pd/Ti/n-InP SBD. The filled circles represent experimentally calculated barrier heights. The open circles represent estimated values of Φ_{ap} using Equation (13) with $\bar{\Phi}_{b0}$ (T = 0 K) = 0.8006 eV and σ_0 = 0.1144 V values.

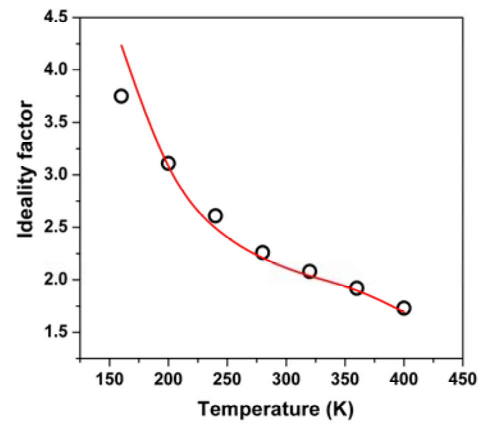

Figure 3. Temperature dependence of the ideality factor for Pd/Ti/n-InP SBD in the range of 160 - 400 K. The open circles shows the experimental ideality factors and continuous curve shows the estimated value of n_{ap} using Equation (14) with ρ_2 = 0.2504 V and ρ_3 = –0.01417 V.

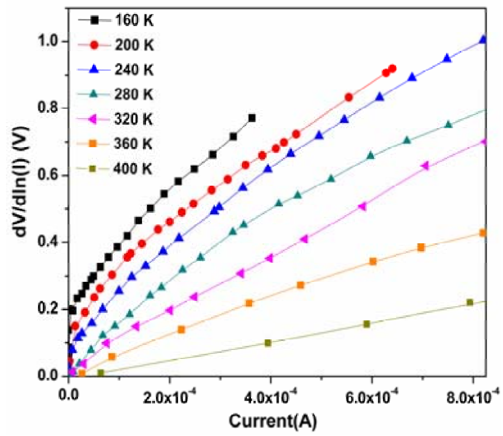

Figure 4. Plot of dV/dln(I) versus I for Pd/Ti/n-InP SBD.

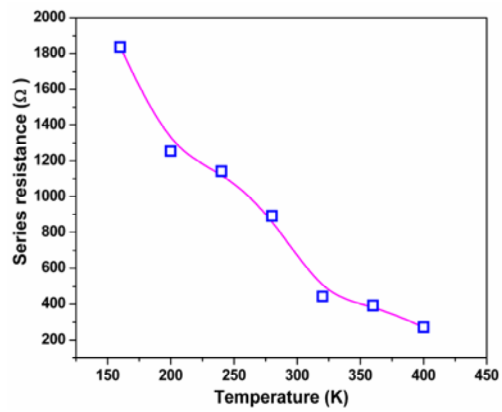

Figure 5. Temperature dependence of series resistance of Pd/Ti/n-InP SBD in the temperature range of 160 - 400 K.

in the temperature range of 160 - 400 K. The resistance of the SBD 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 values of series resistance (R_s) are achieved from the forward bias I-V data using the method developed by Cheung [28]. The forward bias current-voltage characteristics due to thermionic emission of a Schottky contact with the series resistance can be expressed as [1,29]

$$\frac{\mathrm{d}V}{\mathrm{d}(\ln I)} = IR_S + n\left(\frac{kT}{q}\right) \tag{5}$$

Figure 4 shows the plot of dV/d(lnI) versus I as a function of temperature. Equation (5) should give 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(ln$I$) 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 Equation (5) and corresponding values are 1836 Ω at 160 K and 272 Ω at 400 K. It is observed that the series resistance increases with decrease of temperature as shown in **Figure 5**. As can be seen in **Figure 5**, the decrease of R_S with the increasing 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 [30]. The calculated zero-bias BH, ideality factors and series resistance of the Pd/Ti Schottky contacts as a function of temperature is given in the **Table 1**.

For the evaluation of the BH, one may also make use of the Richardson plot of the saturation current. Equation (2) can be written as

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

The plot of $\ln(I_0/T^2)$ versus $10^3/T$ is found to be non-linear in the measured temperature range as shown in **Figure 6**. The non-linearity of the conventional $\ln(I_0/T^2)$ versus $10^3/T$ is caused by the temperature dependence of the BH and ideality factor. The experimental data are seen to fit asymptotically to a straight line at higher temperatures only. According to Equation (6), the plot of $\ln(I_0/T^2)$ versus $10^3/T$ yields a straight line with the slope giving the BH at T = 0 K and the intercept giving the Richardson constant. An activation energy value of 0.27 eV from the slope of this straight line is obtained for the Pd/Ti Schottky contact. 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 **Figure 6** is equal to 2×10^{-3} $A \cdot cm^{-2} \cdot K^{-2}$, which is lower than the known value of 9.4 $A \cdot cm^{-2} \cdot K^{-2}$. The deviation in the Richardson plot may be due to the effects of the image-force, the effect of tunneling current through the potential barrier, the effect of recombination in the space charge region appearing at low voltage and the variation of the charge distribution near the interface [31]. Ac-

Table 1. Ideality factors, series resistances and Schottky barrier heights of Pd/Ti Schottky contact on n-type InP in the temperature range of 160-400 K.

Temperature (K)	Ideality factor (n)	Series resistance (Rs) (Ω)	Barrier heights (eV) Φ_{b0}	(eV) Φ_{C-V}	(eV) Φ_{bf}
160	**3.75**	**1836**	0.35	0.73	1.136
200	**3.11**	**1255**	0.40	0.71	1.074
240	**2.61**	**1143**	0.47	0.69	1.056
280	**2.26**	**893**	0.53	0.68	1.051
320	**2.08**	**442**	0.55	0.65	0.983
360	**1.92**	**392**	0.59	0.63	0.975
400	**1.73**	**272**	0.63	0.61	0.949

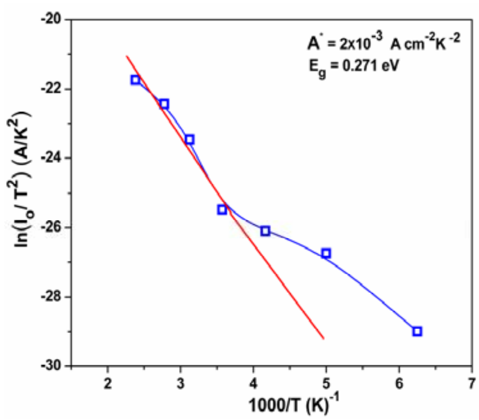

Figure 6. Richardson plot of ln(I_0/T^2) versus 10^3/T for Pd/Ti/n-InP SBD.

cording to Horvath [32], the A^* value obtained from the temperature dependence of the I-V characteristics may be affected by the lateral inhomogeneity of the barrier, and the fact that it is different from the theoretical value may be connected to a value of the real effective mass that is different from the calculated one.

It is observed that ideality factor n is greater than unity which indicates that TE is not the only operative mechanism for current flow and is usually attributed to a SBH which is bias dependent. If the current transport is controlled by the thermionic field emission (TFE) theory, the relation between current and voltage can be expressed as [33,34]

$$I = I_s \exp\left[\frac{V}{E_0}\right] \tag{7}$$

$$\text{with } E_0 = E_{00}\coth\left[\frac{qE_{00}}{kT}\right] = \frac{n_{tun}kT}{q} \tag{8}$$

where E_{oo} is the characteristic energy, which is related to the transmission probability of the carrier through the barrier given by

$$E_{00} = \frac{h}{4\pi}\left(\frac{N_d}{m_e^*\varepsilon_s}\right)^{\frac{1}{2}} \tag{9}$$

where h is the Planck constant ($h = 6.626 \times 10^{-34}$ J·sec), N_d is the donor concentration, ε_s is the semiconductor dielectric constant and m_e^* is the electron effective mass.

In the case of our Pd/Ti/n-InP SBDs with $N_d = 2.63 \times 10^{15}$ cm^{-3} (from C-V method at room temperature), $m_e^* = 0.077\ m_0$ and $\varepsilon_s = 12.4\varepsilon_0$ the value of E_{00} is found to be about 0.9738 meV. When considering the bias coefficient of the barrier height, $\beta = \partial\Phi_b/\partial V$, Equation (8) can be written as [32,35]

$$n_{tun} = \frac{E_0}{kT(1-\beta)} \tag{10}$$

The theoretical temperature dependence of ideality factor for the case when the current through Schottky junction is dominated by the TFE is shown in **Figure 7**. The solid lines in **Figure 7** are obtained by fitting Equation (8) to the experimental temperature dependence values of the ideality factor presented for different values of the characteristic energy E_{oo}, without considering the bias coefficient of the BH, $\beta = 0$, for the Pd/Ti/n-InP SBDs. The filled circles in the **Figure 7** shows the temperature dependence values of ideality factor obtained from the experimental current-voltage (I-V) characteristics. From the **Figure 7**, it is observed that the experimental temperature dependence of ideality factor is in agreement with the curve (C) obtained with E_{oo} = 15 meV for the Pd/Ti/n-InP SBD studied in the temperature range of 160 - 400 K. Hence, there is a significant consistency between the theoretical and experimental characteristics as shown in **Figure 7** (curve C).

The characteristic energy E_{oo} value is much larger than the theoretical value 0.973 meV calculated for n-InP. To understand the possible origin of the high characteristic energy values E_{oo}, it should be underlined that E_{oo} is connected with the transmission probability [36,37]. The characteristic energy has been related to several effects such as the electric field present on the surface of the semiconductor [38], the existence of relatively a thick interfacial insulating layer between the deposited metal and semiconductor and the density of states. Therefore, any mechanism which enhances the electric field or the

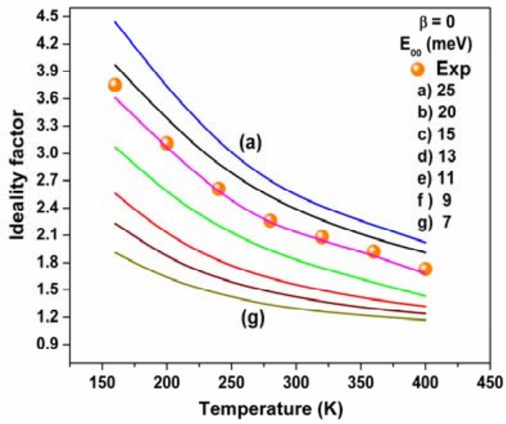

Figure 7. Theoretical temperature dependence of ideality factor for the case when the current through the junctions is dominated by the TFE with characteristic energy values E_{00} according to Equation (8) (Solid lines) for Pd/Ti/n-InP SBD. The filled circles show the experimental temperature dependence values of the ideality factor obtained from I-V characteristics as shown in Figure 1.

density of states at the semiconductor surface will increase the TFE, and so the apparent E_{oo} [32].

Another way to correlate the obtained parameters ideality factor n and barrier height Φ_{bo} is to calculate the flat-band BH Φ_{bf}. The BH decreases with decreasing temperature which is obtained from Equation (3) is called apparent or zero-bias BH. The BH obtained under flat-band condition is called the flat-band BH and is considered as the real essential quantity. In contrast to the case of the zero-bias BH, the electric field in the semiconductor is zero under the flat-band condition and thus the semiconductor bands are flat, which eliminates the effect of tunneling and image force lowering that would affect the I-V characteristics and removes the influence of lateral inhomogeneity [12,20]. The flat-band barrier height (Φ_{bf}) is given by [39,40]

$$\Phi_{bf} = n\Phi_{b0} - (n-1)\left(\frac{kT}{q}\right)\ln\left(\frac{N_c}{N_d}\right) \tag{11}$$

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}. **Figure 2** shows the variation of flat-band barrier height Φ_{bf} as a function of the temperature. However, it is observed that Φ_{bf} increase with decreasing temperature. Similar phenomenon is also reported by the others [20,22]. The temperature dependence of the flat-band barrier height can be expressed as

$$\Phi_{bf}(T) = \Phi_{bf}(T=0) + \alpha T \tag{12}$$

where $\Phi_{bf}(T=0)$ 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 Equation (12) to the experimental data (filled triangles) in **Figure 2** yields Φ_{bf} (T = 0) = 1.24 eV and $\alpha = -7.4285 \times 10^{-4}$ eVK^{-1}.

The ideality factor is simply a manifestation of the barrier uniformity and it increases for an inhomogeneous barrier [41]. A significant increase in the ideality factor and decrease in the SBH at low temperatures are possibly originated by inhomogeneities of thickness, and composition of the layer, non-uniformity of the interfacial charges or the presence of a thin insulating layer between the metal and the semiconductor [9,10,26,39]. Schmitsdorf [42] used Tung's theoretical approach and they found a linear correlation between the experimental zero-bias SBHs and ideality factors. **Figure 8** shows a plot of experimental BHs versus ideality factor with temperature for the Pd/Ti/n-InP Schottky diode. The solid line in the **Figure 8** is the least-squares fit to the experimental data. As can be seen from the **Figure 8**, there is a linear relationship between the experimental effective SBHs and the ideality factors of the Schottky contact. The extrapolation of the experimental BHs versus ideality factor plot to n = 1 has given a homogeneous BH (Φ_{hom}) of approximately 0.71 eV. The other BH values deviate from this value due to local inhomogeneities. A homogeneous BH of approximately 0.71 eV obtained from the extrapolation of the least-square linear fitting to data to n = 1 (**Figure 8**) is in agreement with the value obtained by Ashok *et al.* [23] for the Pd/Pt/n-InP Schottky barrier diodes.

The decrease in the BH with a decrease in temperature can also be explained by the lateral distribution of BH if the BH has a Gaussian distribution of the BH values over the Schottky contact area with the mean BH ($\bar{\Phi}_{b0}$) and standard deviation (σ_0). The standard deviation is a measure of the barrier homogeneity. The Gaussian distribution of the BHs yields the following expression for

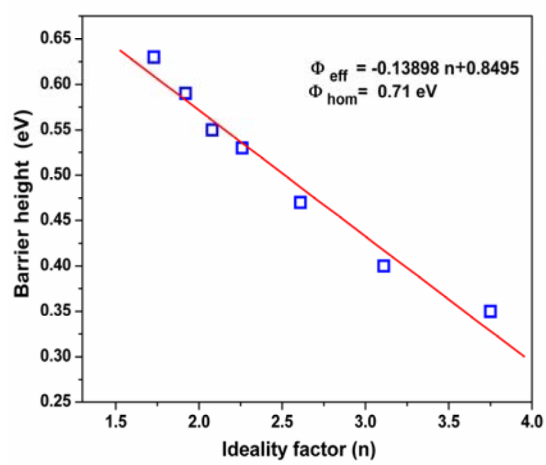

Figure 8. The zero-bias barrier height versus ideality factor for the Pd/Ti/n-InP SBD at different temperatures.

the BH [9,10,12,20,22]

$$\Phi_{ap} = \bar{\Phi}_{b0}(T=0) - \frac{q\sigma_0^2}{2kT} \qquad (13)$$

where Φ_{ap} is the apparent BH measured experimentally. The same expression (Equation (13)) is used already by Song *et al.* [9] and also by Werner and Guttler [10] for the apparent BH construction. Usually the temperature dependence of σ_0 is small and it can be neglected. The observed variation of ideality factor with temperature in the model is given by [10]

$$\left(\frac{1}{n_{ap}} - 1\right) = -\rho_2 + \frac{q\rho_3}{2kT} \qquad (14)$$

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 1/2 kT and n_{ap} versus 1/2 kT plots are shown in **Figure 9**. The linearity in the apparent barrier height or ideality factor versus 1/2 kT curves is in agreement with the recent model which is related to thermionic emission over a Gaussian distribution. The plot of Φ_{bo} versus 1/2 kT is a straight line with the intercept on the ordinate determining the zero mean BH $\bar{\Phi}_{b0}$ (T = 0 K) and the slope gives the standard deviation (σ_0). The corresponding values are 0.80 eV and 114 mV for $\bar{\Phi}_{b0}$ (T = 0) and σ_0 respectively. Moreover, as can be seen in the **Figure 2**, the experimental results of Φ_{ap} fit very well with the theoretical Equation (13) with $\bar{\Phi}_{b0}$ (T = 0) = 0.80 eV and σ_0 = 114 mV. The open circles in **Figure 2** indicates the data estimated with these parameters in using Equation (13) and filled circles indicates the experimental barrier heights measured from I-V characteristics. The observed standard deviation is 14.3% of the mean barrier height. The lower value of standard deviation shows the better rectifying performance with barrier homogeneity.

Figure 9 shows the experimental ideality factor versus 1/2 kT plot is a straight line. The values obtained for ρ_2 and ρ_3 from the intercept and the slopes of the straight line are 0.2504 V and −0.0141 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 SBH. Furthermore, the experimental results of n_{ap} fit very well with theoretical Equation (14) with ρ_2 = 0.2504 V and ρ_3 = –0.0141 V as shown in **Figure 3**. The continuous solid line in the **Figure 3** indicates data estimated with these parameters using Equation (14) and open circles indicates experimental ideality factor values. The lower value of σ_0 corresponds to more homogeneous barrier heights. According to Cavlet

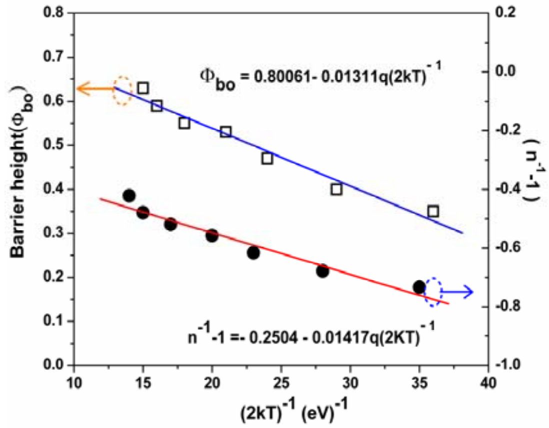

Figure 9. The zero-bias barrier height and ideality factor versus 1/2 kT plots and their linear fits for the Pd/Ti/n-InP SBD according to Gaussian distribution of the barrier heights.

et al. [43], the value of σ_0 (114 mV) is not small compared to the mean value of $\bar{\Phi}_{b0}$ (T = 0) = 0.80 eV 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.

Due to the barrier inhomogeneity at low temperatures, the conventional Richardson plot deviates from linearity. It can be modified by combining Equations (2) and (13) as follows

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2\sigma_0{}^2}{2k^2T^2}\right) = \ln\left(AA^*\right) - \frac{q\bar{\Phi}_{bo}}{kT} \qquad (15)$$

A modified $\ln(I_0/T^2) - (q^2\sigma_0^2/2k^2T^2)$ versus 1000/T plot can be obtained according to Equation (15). The plot should give a straight line with the slope directly yielding the mean barrier height $\bar{\Phi}_{b0}$ (T = 0) and the intercept (= $\ln AA^*$) at the ordinate, determining A^* for a given diode area A. **Figure 10** shows the modified $\ln(I_0/T^2)$ – ($q^2\sigma_0^2/2k^2T^2$) versus 1000/T plot gives $\bar{\Phi}_{b0}$ (T = 0), and A^* as 0.796 eV and 6.16 $A \cdot cm^{-2} \cdot K^{-2}$, respectively, without using the temperature coefficient of the barrier height α. Mean while, this value of $\bar{\Phi}_{b0}$ = 0.796 eV is approximately the same as the value of $\bar{\Phi}_{b0}$ = 0.80 eV from the plot of Φ_{ap} versus 1/2 kT given in **Figure 9**. The modified Richardson constant A^* = 6.16 $A \cdot cm^{-2} \cdot K^{-2}$ is in close agreement with the theoretical value of A^* = 9.4 $A \cdot cm^{-2} \cdot K^{-2}$.

3.2. Analysis of Capactance-Voltage-Temperature (C-V-T) Characteristics

The experimental reverse bias C^{-2}-V characteristics of the Pd/Ti/n-InP SBD in the temperature range of 160 - 400 K in steps of 40 K are shown in **Figure 11**. The

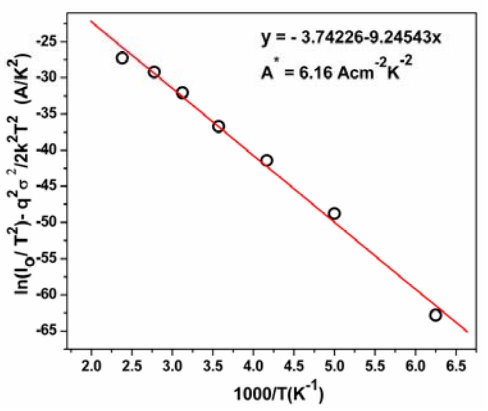

Figure 10. Modified Richardson ln(I_0/T^2)-($q^2\sigma_0^2/2k^2T^2$) versus 1000/T plot for the Pd/Ti/n-InP SBD according to the Gaussian distribution of barrier heights.

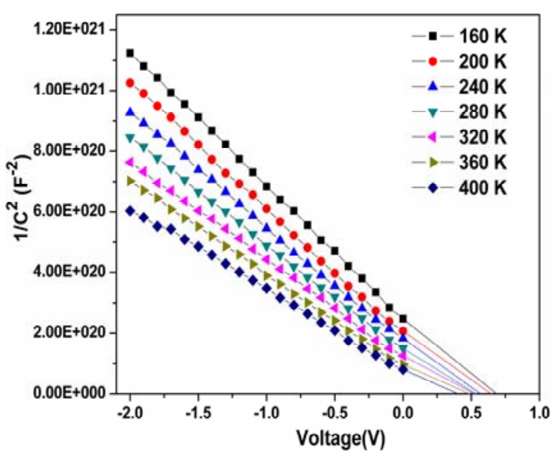

Figure 11. The reverse bias C^{-2}-V characteristics of the Pd/Ti/n-InP SBD in the temperature range of 160 - 400 K.

junction capacitance has been performed at a frequency of 1 MHz. The C-V relationship for Schottky diode is [1,29]

$$\frac{1}{C^2}=\left(\frac{2}{\varepsilon_s qN_d A^2}\right)\left(V_{bi}-\frac{kT}{q}-V\right) \qquad (16)$$

where $\in_s$ is the permittivity of the semiconductor ($\in_s$ = 12.4 $\in_0$) [24], 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 BH is given by the equation $\Phi_{CV} = V_0 + V_n + kT/q$, here $Vn = (kT/q)\ ln (N_c/N_d)$. 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 × 10^{17} cm^{-3} for InP at room temperature [2]. The temperature dependence of the experimental carrier concentration (N_d) is calculated from the slope of reverse bias C^{-2}-V characteristics from **Figure 11** and the values of N_d varied from 1.96 × 10^{15} to 3.11 × 10^{15} cm^{-3} in the temperature range of 160 - 400 K. The values of Nc varied from 2.06 × 10^{17} to 8.22 × 10^{17} cm^{-3} as temperature varied between 160 K and 400 K, respectively. It is observed that carrier concentration for n-InP increased with increase in temperature. The estimated Schottky barrier height of Pd/Ti Schottky contact is in the range of 0.73 eV at 160 K to 0.61 eV at 400 K respectively. It is noted that the barrier height Φ_{CV} increased with decrease in temperature. Furthermore, as can be seen from **Figure 2** it was observed that the Φ_{CV} values are higher than the Φ_{bo} values in the investigated temperature range. This discrepancy could be explained by the existence of an interfacial layer or of trap states in the semiconductor and the existence of Schottky barrier height inhomogeneity [10,11,26]. Due to the square dependence of Φ_{CV} on 1/C, compared to the logarithmic dependence of $\Phi_{I\text{-}V}$ on the current, Φ_{CV} is more sensitive to the experimental error of the measurement data than Φ_{IV} [19]. Moreover, it is clearly seen from the **Figure 2** that Φ_{CV} is obtained to increase with decreasing temperature. The temperature dependence of Φ_{CV} is expressed as

$$\Phi_{CV} = \Phi_{CV}\left(T = 0\mathrm{K}\right) + \alpha T \qquad (17)$$

where Φ_{CV} (T = 0 K) is the barrier height extrapolated to zero temperature and α is the temperature coefficient of the barrier height. The linear fit of Equation (17) to the experimental data (filled squares) in **Figure 2** yields Φ_{CV} (T = 0 K) = 0.8114 eV and α = –5.1 × 10^{-4} eVK^{-1} which is the temperature coefficient of the InP band gap [44].

Furthermore, it can be seen that the apparent barrier height from the experimental forward bias I-V plot is also related to the mean barrier height $\bar{\Phi}_{b0} = \bar{\Phi}_{CV}$ from the experimental reverse bias C^{-2}-V plot [10,40]. The capacitance depends only on the mean band bending and is insensitive to the standard deviation σ_0 of the barrier distribution [10,40]. The relationship between Φ_{ap} and Φ_{CV} is given by [10,40]

$$\Phi_{CV} - \Phi_{ap} = -\frac{q\sigma_0^{\,2}\left(T=0\right)}{2kT} + \frac{q\alpha_\sigma}{2k} \qquad (18)$$

where α_σ is attributed to the temperature dependence of σ_0. **Figure 12** shows the experimental (Φ_{CV}-Φ_{IV}) versus $1/T$ plot according to Equation (18). The plot should give a straight line of the slope $\sigma_0^2/2k$ and a y-axis intercept $\alpha_\sigma/2k$ from which the parameters σ_0 and α_σ can be determined. The slope and y-axis intercept of the plot given the values of σ_0 = 149 mV and α_σ = 5.59 × 10^{-5} V$^2\cdot$K^{-1}, respectively. The value of σ_0 in the investigated temperature region is in close agreement with the value of σ_0 = 114 mV from the plot of Φ_{ap} versus 1/2

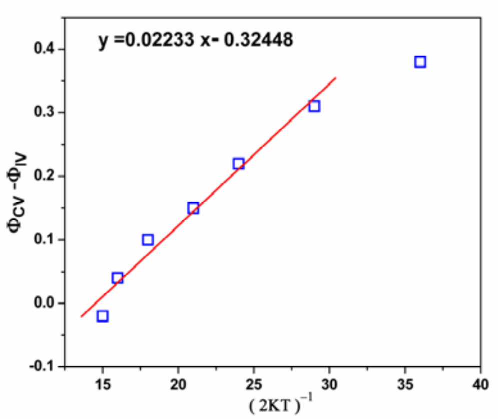

Figure 12. Barrier height difference between values as derived from the conventional evaluation of I-V and C-V data as a function of inverse temperature.

kT given in **Figure 9** which is not small when compared to the mean BH value of 0.796 eV. Therefore, these significantly large potential fluctuations drastically affect low temperature I-V data and, in particular, they could be responsible for the curved behaviour of the conventional Richardson plot as shown in **Figure 6**.

4. Conclusions

In this paper, the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of Pd/Ti/n-InP SBDs have been investigated in the temperature range 160 - 400 K. The electrical parameters such as ideality factor (n) and zero-bias BH (Φ_{bo}) are found to be strongly temperature dependent. It is found that the ideality factor (n) of the diode decreases while the corresponding zero-bias SBH increasing with an increase in temperature. The values of series resistance (R_s) estimated from Cheung's method were strongly temperature dependent. The flat-band barrier height values are obtained from the temperature dependence of the I-V characteristics and the values are in the range 1.13 - 0.94 eV. The laterally homogeneous SBH value is approximately 0.71 eV for the Pd/Ti/n-InP SBD which is deduced from the linear relationship between the experimental BHs and ideality factors. The mean BH ($\bar{\Phi}_{b0}$) and effective Richardson constant A^* are found as 0.796 eV and 6.16 $\mathrm{Acm^{-2}K^{-2}}$, respectively, from a modified $\ln(I_0/T^2) - (q^2\sigma_0^2/2k^2T^2)$ versus 1000/T plot. 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 $n_{ap.}$ It can be concluded that the temperature dependent current-voltage (I-V) and capacitance-voltage (C-V) characteristic of the Pd/Ti/n-InP Schottky barrier diodes over a wide temperature range have been explained on the basis of thermionic emission mechanism by assuming the presence of Gaussian distribution of barrier heights.

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