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Temperature dependency and current transport mechanisms of Pd/V/n-type InP schottky rectifiers

S. Sankar Naik[*], **V. Rajagopal Reddy**

Department of Physics, Sri Venkateswara University, Tirupati 517 502, India

[*]Corresponding author. Tel: (+91) 9966918156; Fax: (+91) 877-2249666; E-mail: shankarnaik.phd@gmail.com

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ABSTRACT

We have investigated the temperature-dependent current-voltage (I-V) and capacitance-voltage (C-V) characteristics of Pd/V Schottky contacts on n-type InP in the temperature range of 200-400 K. The estimated barrier height for the Pd/V/n-type InP SBDs from the I-V and C-V characteristics have varied from 0.48 eV to 0.65 eV (I-V) and 0.85 eV to 0.69 eV (C-V), and the ideality factor (n) from 4.87 to 1.58 in the temperature range 200 to 400 K. It has been observed that the ideality factor decreases while the barrier height increases with increase of temperature. Such behaviour is attributed to barrier inhomogeneities by assuming a Gaussian distribution of barrier heights at the interface. Further, it is found that the series resistance (R_S) values of Pd/V/n-InP Schottky diode estimated from Cheung's function are strongly temperature dependent. The zero-bias barrier height ϕ_{bo} versus 1/2kT plot has been drawn to obtain the evidence of a Gaussian distribution of the barrier height. The estimated value of $\overline{\phi}_{bo}$ is 0.89 eV with standard deviation σ_o=145 meV. The mean barrier height and the Richardson constant are determined by the modified Richardson plot $\ln(I_o/T^2)-(q^2\sigma^2_o/2k^2T^2)$ versus 1/T and are respectively 0.72 eV and 6.59 $Acm^{-2}K^{-2}$ respectively. Also, the discrepancy between the BHs obtained from the I-V and C-V characteristics is discussed. The interface state densities extracted for the Pd/V/n-InP Schottky diode are in the range of 5.14×10^{12} to 3.21×10^{12} $eV^{-1}cm^{-2}$ in the bandgap below conduction band form E_C-0.25 to E_C-0.51 eV. Copyright © 2012 VBRI Press.

Keywords: Schottky diodes; indium phosphide; gaussian distribution; barrier height inhomogeneity; interface state density.

S. Sankar Naik was born in Madakasira, Andhra Pradesh, India in 1984. He received the M.Sc. Degree from Sri Krishnadevaraya University, Anantapur, India in 2007 and M. Phil. Degree from Sri Venkateswara University, Tirupati, India in 2010. He is recipient of UGC-RGNF, Senior Research Fellowship, New Delhi, India. Currently, he is pursuing Ph.D in the field of semiconductor Physics. During his research period, he has published more than six papers in the refereed international journals. He has presented four papers in international conferences and five papers in national conference. His research work mainly focuses on the fabrication and characterization of high quality Ohmic and Schottky contacts to compound semiconductors (InP) for microelectronic device applications.

V. Rajagopal Reddy received the M.Sc and Ph.D degrees in Physics from Sri Venkateswara University, Tirupati, India in 1989 and 1994. From September 2002 to December 2003, Prof. Reddy was a Visiting Research Professor, at the Semiconductor Thin Film and Device laboratory, Gwanju Institute of Science and Technology, Gwanju, Korea, where he performed research on Ohmic and Schottky Contacts to wide band gap semiconductors (GaN). Prof. Reddy has published more than 110 articles in referred journals, and has been author or co-author of over 65 conference papers. Prof. Reddy has successfully guided 11 Ph.Ds in the field of Advanced Electronic Materials (GaN). He has also acted as paper referee for some Internationals journals. He is holder of one Korean patent. He is also actively involved in Major Research Projects sponsored by UGC and DST, New Delhi, India. His current research interests are (i) Ohmic and Schottky Contacts to wide-band gap semiconductors, (ii) Surface analysis of III-V and II-VI semiconductors, and (iii) Deep level studies in wide band gap semiconductors such as GaN, ZnO.

Introduction

Schottky barrier diodes (SBDs) are the most simple metal-semiconductor (MS) contact devices due to their technological importance [**1-2**]. Indium phosphide (InP) is a useful substrate for opto-electronic and high-speed electronic device applications due to direct transition bandgap and high electron mobility, both of which are very important in these devices [**3**]. Although Schottky interfaces have been well studied for over 50 years, it is only in the past decade that inhomogeneous contact has been considered as an explanation for voltage dependent barrier height [**4**]. The barrier height (BH) is likely to be a function of the interface atomic structure and the atomic inhomogeneities at a metal-semiconductor (MS) interface which are caused by grain boundaries, multiple phases, defects, a mixture of different phases etc [**5**]. Therefore, the analysis of the current-voltage (I-V) characteristics of the SBDs at room temperature alone does not give detailed information about their conduction process or the nature of barrier formation at the MS interface [**5, 6-7**]. Moreover, the SBDs play an important role in devices operating at cryogenic temperatures as infrared detectors, sensors in thermal imaging, microwave diodes, infrared and nuclear particle detectors [**8**]. The temperature dependence of electrical characteristics of the Schottky contacts provides the information regarding the charge transport process through metal-semiconductor contacts and also gives a better picture of the conduction mechanisms [**9-10**]. Specifically, it is shown that the leakages, edge-related currents, greater-than-unity ideality factors and other dependence of ideality factor on temperature and dependence of the measurement techniques are all natural consequences of SBH inhomogeneity [**11**]. The analysis of the current-voltage (I-V) characteristics of Schottky barriers on the basis of thermionic emission diffusion (TED) theory reveals an abnormal decrease of the barrier height (BH) and the increase of the ideality factor with decreasing temperature [**12-14**]. The decrease in the SBH at low temperatures leads to nonlinearity in the activation energy ln (I_o/T^2) versus 1/T plot. These finding have been satisfactorily explained recently by incorporating the concept of barrier inhomogeneities and introducing thermionic emission mechanism [**11, 15**]. However, the explanation of the possible origin of such anomalies have been proposed by taking into account the interface state density distribution [**16**], quantam-mechanical tunneling [**17**], image force lowering and the lateral distribution of BH inhomogeneities [**18**]. In addition, a Gaussian distribution of the BH over the contact area has been assumed to describe the inhomogeneities as another way too [**19**].

Effort has been made by several groups to form Schottky contacts on n-type InP using a number of different metals. Cetin et al [**20**] studied temperature dependence of electrical characteristics of Au/InP Schottky barrier diode and observed that the ideality factor decreases while the barrier height increases with increase of temperature. Cimilli et al **[21]** investigated Au/n-InP Schottky barrier diodes and reported that the barrier height varies from 0.557 eV to 0.615 eV and the ideality factor from 1.002 to 1.087. Cimilli et al [**22**] evaluated the temperature dependent current-voltage characteristics of the Au/n-InP diode with inhomogeneous Schottky barrier height in the temperature range of 70-300K. Soylu and Abay [**23**] evaluated the barrier characteristics of gold (Au) Schottky contacts on moderately doped n-InP in the temperature range 60-300K. They observed that the ideality factor ‘n’ of the diode decreases while the corresponding zero-bias SBH increases with the increase in temperature. Cetin and Ayyildiz [**24**] reported that the effective barrier heights of the Au and Cu/n-InP SBDs were 0.480 (I-V), 0.524 (C-V) and 0.404 (I-V), 0.453(C-V) respectively. They explained the discrepancy between the barrier height obtained from I-V and C-V method in terms of barrier height inhomogeneity approach. Recently Shankar Naik et al [**25**] investigated the current-voltage-temperature (I-V-T) and capacitance-voltage-temperature (C-V-T) characteristics of Ni/Au Schottky contacts on n-type InP in the temperature range 210-420 K. They reported that the estimated Schottky barrier height of a Ni/Au Schottky contact is in the range 0.38 eV (I-V), 0.93 eV (C-V) at 210 K and 0.70 eV (I-V), 0.73 eV (C-V) at 420 K.

To the best of our knowledge, Pd/V metal scheme has not been explored as Schottky contacts on n-type InP. Therefore, the main aim of the present work is to fabricate and characterize Pd/V Schottky contacts on n-type InP as a function of temperature. In this work, vanadium (V) is selected as first contact layer because it has a work function of 4.3 eV, which is close to that of n-InP, as well as to provide the lowest forward voltage drop. The transition metal palladium (Pd) is selected as a second contact layer because of its high work function and its interaction with InP during electron beam evaporation deposition [**26**], resulting in the enhancement of the barrier height. In the present study, Pd/V Schottky barriers are fabricated on n-InP substrate. The temperature-dependent I-V characteristics of the Pd/V/n-InP Schottky diode have been measured over the temperature range 200-400 K with a temperature step of 40 K. An increase in ideality factor, decrease in barrier height and significant deviations from linearity in the Richardson plots are observed with decrease in temperature for the diode. These anomalies have been explained by TE mechanism by assuming Gaussian distribution of barrier heights and by quantum mechanical tunneling including the thermionic field emission (TFE).

Experimental

Liquid encapsulated czochralski (LEC) grown undoped n-InP wafer was employed in this work. The carrier concentration is about 4.5×10^{15} cm^{-3}. The wafers were initially degreased with organic solvents like trichloroethylene, acetone, and methanol by means of ultrasonic agitation for 5 min in each step, to remove the undesirable impurities, followed by rinsing in deionized (DI) water. Then, the samples were etched with HF (49%) and H_2O (1:10) to remove the native oxide from the substrate. Indium (99.999%, Aldrich) (thickness 500 Å) was deposited on the rough side of the InP wafer as an ohmic contact prior to Schottky diode fabrication at a pressure of 6×10^{-6} mbar and then annealed at 350 ^oC for 1 min in N_2 atmosphere. For making Schottky contacts, the metals V/Pd ((vanadium (99.7%, Aldrich) as a first layer and palladium (99.98%, Aldrich) as second layer)) of 200/300 Å thickness through a stainless mask of diameter 0.7 mm were deposited on the polished side of the InP wafer. In order to reduce irradiation by stray electrons during evaporation, the InP material was screened from electrons originating at the filament of the electron beam evaporator [**27**].

The current-voltage (I-V) and capacitance-voltage (C-V) measurements of the Pd/V Schottky device were made using Keithley source measuring unit (2400) and automated deep level spectrometer (SEMILAB DLS-83D) over the temperature range of 200-400K in steps of 40 K in the dark by using temperature controller DLS-83D-1 cryostat with an accuracy of ± 1K.

Results and discussion

The current-voltage (I-V) measurements

The forward bias current through uniform metal-semiconductor interfaces due to themionic emission (TE) theory can be expressed as [**1**]

$$I = I_o \exp\left(\frac{q(V-IR)}{nkT}\right)\left[1-\exp\left(-\frac{q(V-IR)}{kT}\right)\right] \qquad (1)$$

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

$$I_o = AA^{**} \exp\left(\frac{-q\phi_{bo}}{kT}\right) \qquad (2)$$

Once I_o is determined, the barrier height ϕ_{bo} can be evaluated using given equation

$$\phi_{bo} = \frac{kT}{q}\ln\left[\frac{AA^{**}T^2}{I_o}\right] \qquad (3)$$

where ϕ_{bo} is the zero-bias barrier height, q is the electron charge, k is the Boltzmann constant, T is the absolute temperature, V is the forward-bias voltage, A is the effective diode area, A^{**} is the effective Richardson constant of 9.4 $Acm^{-2}k^{-2}$ [**28**] and R is the series resistance of the neutral region of the semiconductor bulk (between the depletion region and ohmic contact). From equation (1), the ideality factor 'n' can be written as

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

The electrical I-V measurements of the Pd/V/n-InP Schottky diode are made in the temperature range of 200-400K with a temperature step of 40K as shown in **Fig. 1**. The experimental values of the BH and ideality factor are determined from intercepts and slopes of the forward bias ln(I) versus voltage (V) plot according to TE theory. The values of barrier height and ideality factor have been changed from 0.48 eV and 4.87 (at 200 K) to 0.65 eV and 1.58 (at 400 K) respectively. **Figure 2** shows the experimental values of n (indicated by filled circles) and ϕ_{bo} (indicated by filled triangles) as a function of temperature in the temperature range of 200-400K. It can be seen from **Fig. 2**, that both parameters exhibit strong temperature dependence that is the zero-bias barrier height decreases and ideality factor increases with decrease in temperature. Since 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 flowing through the patches of lower SBH and a large ideality factor. As the temperature increases, more and more electrons have sufficient energy to surmount the higher barrier. As a result, the dominant BH increases with temperature and bias voltage [**8**]. The high values of ideality factor are probably due to potential drop in the interfacial layer and presence of excess current and the recombination current through the interfacial states between the semiconductor/insulator layers [**29**].

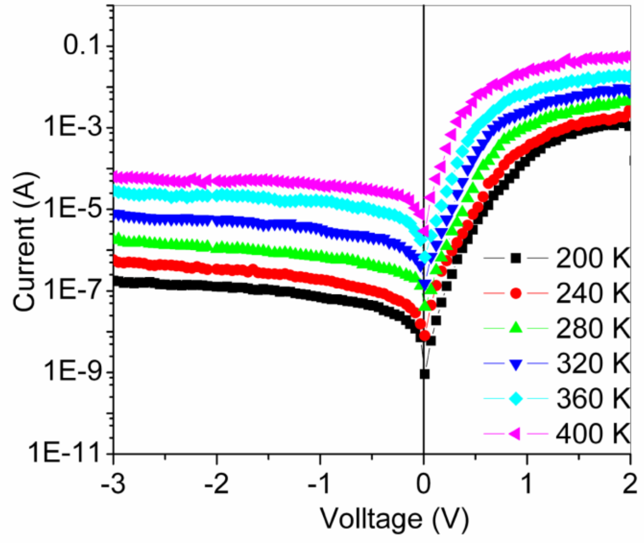

Fig. 1. Experimental current-voltage (I-V) characteristics of a Pd/V/n-InP Schottky diode at various temperatures.

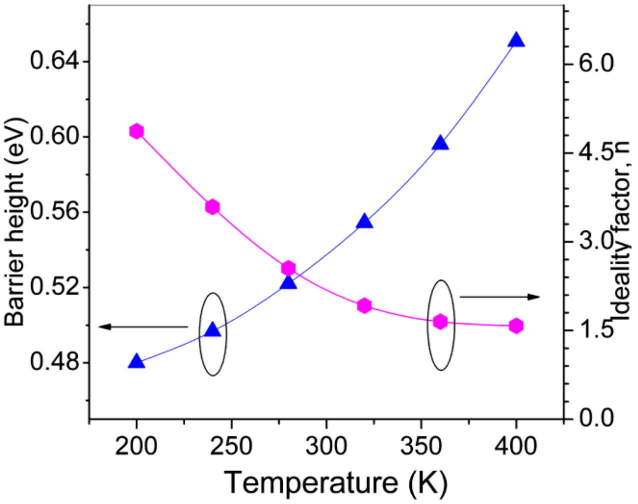

Fig. 2. Temperature dependence of the ideality factor (the filled circles) and barrier height (the filled triangles) for the Pd/V/n-InP Schottky contact.

Usually, 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, the interfacial insulator layer and the interface states when the applied voltage is sufficiently large. Temperature dependency and the series resistance effect on the I-V characteristics of the Pd/V/n-InP Schottky diodes are investigated in the temperature range 200-400K. 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 resistance is calculated using two different methods developed by Cheung-Cheung [**30**] in the high current range where the I-V characteristics are not linear. The forward bias I-V characteristics due to the thermionic emission of Schottky diode with the series resistance can be expressed as [**30, 31**]

$$I = I_o \exp\left[\frac{q(V - IR_S)}{nkT}\right] \tag{5}$$

where the IR_S term is the voltage drop across series resistance of device. The values of the series resistance can be determined from following functions using equation (5)

$$\frac{dV}{d\ln(I)} = IR_S + n\left(\frac{kT}{q}\right) \tag{6}$$

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I}{AA^{**}T^2}\right) \tag{7}$$

and H(I) is given as follows:

$$H(I) = IR_S + n\phi_{bo} \tag{8}$$

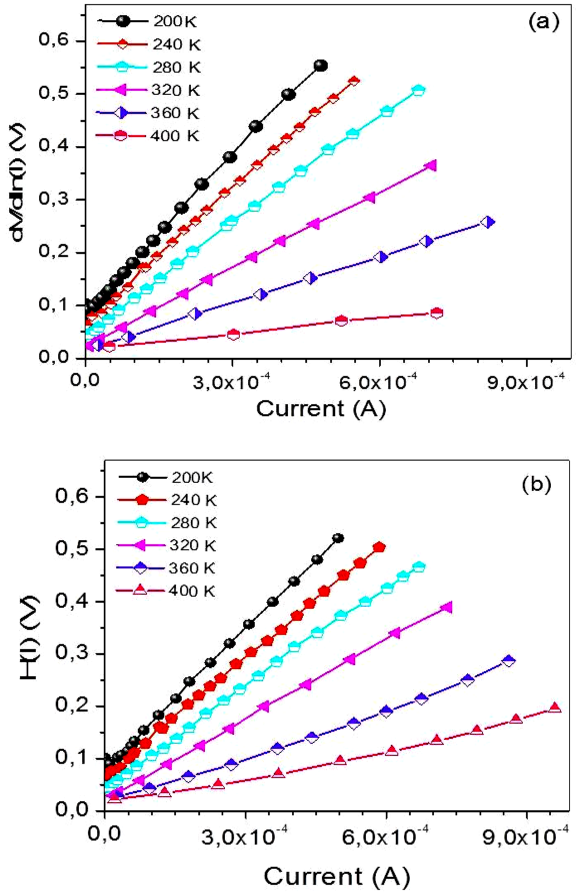

Fig. 3. (a) Plots of dV/dln(I) versus I and (b) H(I) versus I for Pd/V/n-InP Schottky diode.

Fig. 3a experimental dV/d(lnI) versus I and H(I) versus I plots as a function of temperature are presented for Pd/V/n-InP Schottky diode. Equation (6) exhibits a straight line region where the series resistance dominates, for the data in the downward-curvature region of the forward bias I-V characteristics. Thus the plot of dV/d(lnI) versus I will give R_S as the slope and nkT/q as the y-intercept. The data of the downward-curvature region in equation (7) used ideality factor n which is determined from equation (6) is plotted, H(I) versus I in **Fig. 3b**. A plot of H(I) versus I will also lead to a straight line (**Fig. 3b**) with the y-axis intercept being equal to $n\phi_{bo}$. It can be seen obviously that the value of R_S obtained from H(I) versus I plot is in close agreement with the value obtained from dV/d(lnI) versus I plot (**Fig. 3a**). This case shows the consistency of the Cheung's approach. The series resistance R_s obtained for each temperature of the I-V data increases with decrease of temperature. The increase of R_s with the fall of temperature is believed to be due to factors responsible for increase of n, and lack of free carrier concentration at low temperatures [**32**].

For the evaluation of barrier height, one may also make use of the Richardson plot of the saturation current, equation (3) can be rewritten as

$$\ln\left(\frac{I_o}{T^2}\right) = \ln\left(AA^{**}\right) - \frac{q\phi_{bo}}{kT} \tag{9}$$

The saturation current I_o is found from the intercept of the straight lines with ordinate (**Fig. 1**). The plot of ln (I_o/T^2) versus 1000/T is found to be non-linear in the measured temperature (insert in **Fig. 4**) and is due to the temperature dependence of the barrier height and ideality factor. Similar results have also been reported earlier [**12, 32**]. The experimental data are shown to fit asymptotically with a straight line at higher temperatures only. According to equation (9), the plot ln (I_o/T^2) versus 1/T yields a straight line whose slope gives barrier height at 0 K and the intercept gives the Richardson constant. An activation energy value of 0.53 eV is obtained from the intercept of the straight line portion of curve. The value of A^{**} obtained from the intercept of the straight portion of the ordinate and is equal to 4.25×10^{-6} $\text{Acm}^{-2}\text{K}^{-2}$, which is lower than the known value of 9.4 $\text{Acm}^{-2}\text{K}^{-2}$. The deviation in the Richardson plots may be due to the spatially inhomogeneous BHs and potential fluctuations at the interface that consist of low and high barrier areas and hence the current through the diode will flow preferentially through the lower barriers in the potential distribution [**6**]. As explained by Horwath [**33**], the A^{**} value obtained from the temperature dependence of I-V characteristics may be affected by lateral inhomogeneity of the barrier and the fact that it is different from theoretical value.

Since the conventional Richardson plot deviates from the linearity at low temperatures due to the barrier inhomogeneity, equation (9) can be modified as

$$\ln\left(\frac{I_o}{T^2}\right) - \left(\frac{q^2\sigma_o^2}{2k^2T^2}\right) = \ln(AA^{**}) - \frac{q\phi_{bo}}{kT} \tag{10}$$

Hence, the modified Richardson plot

$\ln\left(\frac{I_o}{T^2}\right)-\left(\frac{q^2\sigma_o^2}{2k^2T^2}\right)$ Vs. 1/T according to equation (10) should also be a straight line with the slope and the intercept at the ordinate directly yielding the zero-bias mean barrier height. The best linear fitting to these modified experimental data are depicted in **Fig. 4**. By the least-square linear fitting of the data ϕ_{bo} = 0.72 eV and A^{**} = 6.59 $Acm^{-2}K^{-2}$ are obtained. The calculated Richardson constant value is close to the theoretical value of 9.4 $Acm^{-2}K^{-2}$ for n-type InP.

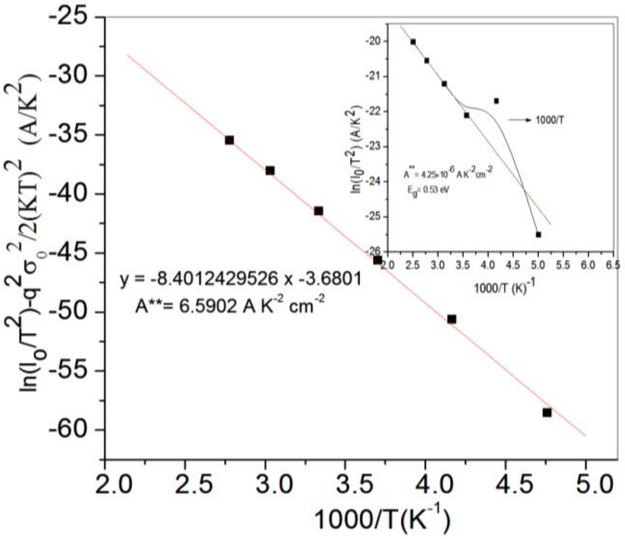

Fig. 4. Modified Richardson $\ln(I_o/T^2)$-$(q^2\sigma^2_o/2K^2T^2)$ versus 1/T plot for the device Pd/V/n-InP Schottky diode according to Gaussian distribution of the barrier heights (insert figure conventional Richardson plot).

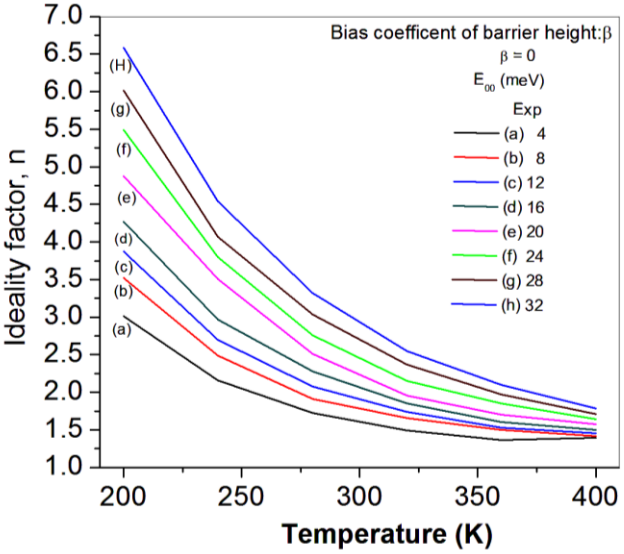

Fig. 5. Theoretical temperature dependence of ideality factor according to equation (12), the bias coefficient of the barrier height, β=0**,** the closed triangles show the experimental temperature dependence values of ideality factor obtained from the current–voltage characteristics.

As mentioned earlier, the similar temperature dependency of ideality factor and zero-bias barrier heights is usually explained by the lateral distribution of barrier heights [**5, 8, 16**]. In most cases, the Gaussian distribution of barrier height is considered. It has been shown that these parameters and their functions can also be explained by the dominance of thermionic field emission TFE [**34**]. However, one can not distinguish between the two possible origins on the basis of the I-V characteristics alone, that is the domination of TFE can be connected with the lateral distribution of barrier height. The enhancement of the transmission probability can be due to the local enhancement of electric field which can also yield a local reduction of the barrier height. If the current transport is controlled by the TFE theory due to the local enhancement of electric field which can also yield a local reduction of the barrier height, the relationship between the current and voltage can be expressed [1] as-

$$I = I_0 \exp\left(\frac{qV}{E_0}\right) \tag{11}$$

$$n_{tun} = \frac{E_{00}}{kT}\coth\left(\frac{E_{00}}{kT}\right) = \frac{E_0}{kT} \tag{12}$$

where E_{00} is the characteristic tunneling energy that is related to the tunnel effect transmission probability

$$E_{00} = \frac{h}{4\pi}\left(\frac{N_a}{m^*\varepsilon_s}\right)^{1/2} \tag{13}$$

where h = 6.625 × 10^{-34} Js, in the case of the n-type InP with carrier concentration of 4.5 × 10^{15} cm^{-3}, $m^* = 0.077m_0$ and $\varepsilon_s = 12.4\ \varepsilon_o$ [**35**], and E_{00} was found to be 1.405 meV. When the bias coefficient of the BH,

$\beta = \frac{\partial\phi_{bo}}{\partial V}$ is considered, equation (12) can be written as

$$n_{tun} = \frac{E_{00}}{kT(1-\beta)} \tag{14}$$

Fig. 5 represents the theoretical temperature dependence of ideality factor in the case when the current through Schottky junction is dominated by the TFE. The solid lines in **Fig. 5** are obtained by fitting equation (14) to the experimental temperature dependence values of the ideality factor presented for different values of the characteristics energy E_{00} without considering the bias coefficient of the barrier height, β = 0.

The closed triangles in **Fig. 5** show the temperature dependence value of ideality factor obtained from the experimental current-voltage characteristics in **Fig. 1**. It can be seen from the **Fig. 5**, the experimental temperature dependence of ideality factor is in agreement with the curve (e) with E_{00} = 20 meV over the whole temperature range.

The value of characteristic energy E_{00} is much higher than the theoretical value of 1.405 meV. Such a difference between the theoretical and experimental values is usually observed and expected for Schottky diodes and the case is connected with local enhancement of electric field which can also yield a local reduction of the barrier height. According to Tung it is mentioned that the behaviour usually attributed to the TFE is not necessarily the conduction mechanism even though tunneling should dominate the electron conduction at heavily doped MS contacts, whenever an ideality factor dependency is observed in **Fig. 5**. The widely varying dependencies of the ideality factor can originate from the same transport mechanism, e.g. thermionic emission, when the SBH is inhomogeneous. These facts do not imply that the conduction mechanism at the SBDs is exclusively thermionic emission, but rather that the ideality factor dependency can not be used as the only criterion for the determination of the conduction mechanism [**16**].

The decrease in the barrier height with a decrease in temperature can also be explained by the lateral distribution of the barrier of BH, provided the barrier height has a Gaussian distribution of the barrier height values over the Schottky contact area with the mean barrier height $\bar{\phi}_{bo}$ and standard deviation σ_0. The standard deviation is a measure of the barrier inhomogeneity. The Gaussian distribution of the BH yields the following expression for the BH [**36-37**]

$$\phi_{b0} = \bar{\phi}_{b0}(T=0)\frac{q\sigma_0^2}{2kT} \tag{15}$$

where $\bar{\phi}_{bo}$ and σ_0 are the Gaussian parameters of the barrier height distribution. The earlier expression for the barrier height construction was used already by [**5**]. The temperature dependence of σ_0 is usually small and can be neglected. The observed variation of ideality factor with temperature is given by

$$\left(\frac{1}{n}-1\right) = -\rho_2 + \frac{q\rho_3}{2kT} \tag{16}$$

where n is the ideality factor (experimental data) and the coefficients ρ_2 and ρ_3 quantify the voltage determination of the BH distribution. The experimental ϕ_{bo} versus 1/T plots drawn by means of the experimental data obtained from **Fig. 1** are given in **Fig. 6** for the temperature range of 200-400K. The linearity of the barrier height (experimental data) or ideality factor versus 1/T curves in **Fig. 6** shows that the temperature dependent experimental data of the Pd/V Schottky contact, are in agreement with the recent model which is related to thermionic emission over a Gaussian BH distribution [**4, 5**]. The plot of ϕ_{bo} versus 1/T (**Fig. 6**) should be straight line with the intercept at the ordinate determining the zero-bias mean BH ($\bar{\phi}_{bo}$) and a slope giving the standard deviation σ_0. According to **Fig. 6**, the value of $\bar{\phi}_{bo}$ = 0.89 eV and σ_0 = 145 meV are obtained from the ϕ_{bo} versus 1/T plot and in the same **Fig 6**, the plot of 'n' versus 1/T must be a straight line that gives voltage coefficients ρ_2 and ρ_3 from the intercept and slope of the curve respectively. The values of ρ_2 = -0.026 and ρ_3 = 0.076 are obtained from the experimental n versus 1/T plot. Meanwhile, the Gaussian distribution of barrier height $\bar{\phi}_{bo}$ = 0.89 eV is nearly the same as the value of mean barrier height ϕ_{bo} = 0.72 eV from the plot of $\ln\left(\frac{I_0}{T^2}\right)-\left(\frac{q^2\sigma_0^2}{2k^2T^2}\right)$ versus 1000/T shown in **Fig. 4.** These results show that the temperature dependent I-V characteristics of Pd/V/n-InP Schottky structure obey the Gaussian distribution of barrier height.

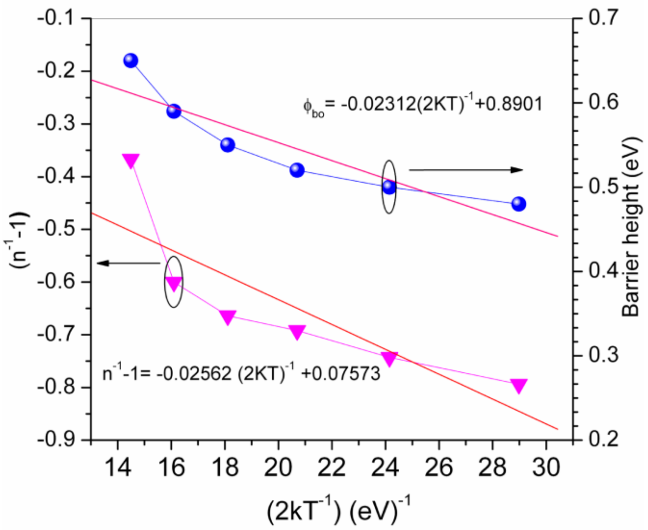

Fig. 6. Zero-bias barrier height and ideality factor versus 1/(2kT) curves of the Pd/V/n-InP Schottky diode according to Gaussian distributions of the barrier height.

Capacitance-voltage (C-V) measurements

The experimental C-V characteristics have been analyzed using the Schottky-Mott equation [1]-

$$C = \sqrt{\frac{q\varepsilon_S N_d A^2}{2(V_{bi}-V-V_T)}} \tag{17}$$

where ε_S is the dielectric constant of the semiconductor, A is the area of the Schottky contact, N_d is the concentration of ionized donor atoms, V_{bi} is the built-in potential, V_T(=kT/q) is the thermal voltage and V is the applied reverse bias. Using equation (17) the value of N_d may be written as-

$$N_d = \frac{2}{q\varepsilon_S A^2}\left[-\frac{1}{\left(d\left(1/C^2\right)/dV\right)}\right] \tag{18}$$

From the slope of $1/C^2$ versus V curve the value of ionized donor concentration N_d can be obtained. The SBH ϕ_{bo}^{C-V} is related to the built-in voltage V_{bi} by the following equation

$$\phi_{bo}^{C-V} = V_{bi} + \frac{kT}{q}\ln\left(\frac{N_C}{N_d}\right) \tag{19}$$

$$N_C = 2\left(\frac{\left(2m^{*}kT\right)^{3/2}}{h^3}\right) \tag{20}$$

where N_c is the effective density of states in InP conduction band and N_d is the donor concentration, $m^*=0.078m_o$ is the effective mass of the electrons in InP and m_o is the rest mass of electron [**1**]. From the intercept of the $1/C^2$ versus V curve on the voltage axis, the value of V_{bi} is calculated.

The experimental reverse bias $1/C^2$ versus V characteristics of Pd/V/n-InP Schottky diode over the temperature range 200-400 K in steps of 40 K are shown in **Fig. 7**. The junction capacitance has been measured at a frequency of 1 MHz. The capacitance of the diode in the voltage range of 0.0 to -2.0 V has increased with increasing temperature. Furthermore, the linear behaviour of the curves can be explained by the factors that the interface states and the inversion layer charge cannot follow the a.c. signal at 1 MHz and accordingly do not contribute appreciably to the diode capacitance. Moreover, the temperature dependence of the experimental donor concentration was evaluated from the reverse bias $1/C^2$ versus V characteristics.

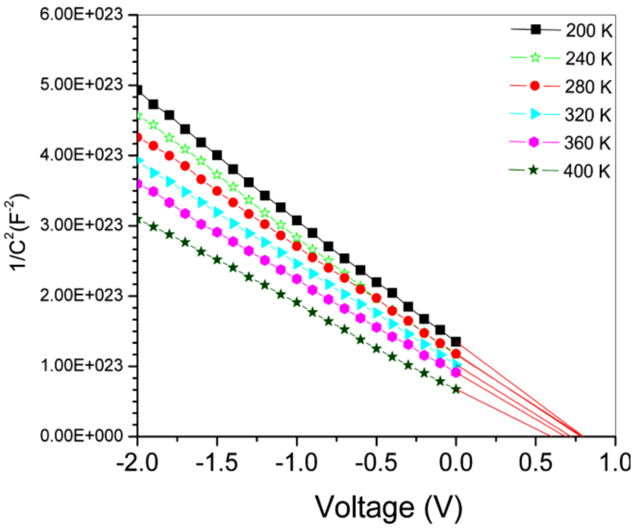

Fig. 7. Temperature dependence of the donor concentration from experimental reverse bias C^{-2}-V characteristics for the Pd/V/n-InP Schottky diode.

The values of N_d varied from 4.844×10^{15} to 7.029×10^{15} cm^{-3} for the Pd/V/n-InP Schottky diode over the temperature range between 200 and 400 K. It is observed that the donor concentration (N_d) of the n-InP increases with increase in temperature is shown in **Fig. 8**. Measurements showed that the SBH (ϕ_{bo}^{C-V}) values of the Pd/V/n-InP Schottky diodes are 0.85 eV at 200 K and 0.69 eV at 400 K, respectively. The value of the barrier height extracted from the C-V curves is higher than obtained from the I-V measurements. This result may be expected from non-ideal Schottky diodes. The barrier height (I-V and C-V), ideality factor and series resistance of the Pd/V Schottky contact as a function of temperature are given in the **Table 1**.

Table 1. Ideality factor, series resistance and Schottky barrier heights of Pd/V/n-InP Schottky diode in the temperature range of 200-400 K.

T	Ideality factor	Series resistance (Ω)		Barrier height	
(K)	(n)	dV/dln(I)	H(I)	ϕ_{bo}^{I-V} (eV)	ϕ_{bo}^{C-V} (eV)
200	4.87	970	961	0.48	0.85
240	3.58	869	838	0.50	0.83
280	2.55	691	681	0.52	0.79
320	1.92	501	488	0.55	0.77
360	1.64	306	293	0.59	0.74
400	1.58	98	93	0.65	0.69

As can be seen from **Table 1**, it is observed that the ϕ_{C-V} values are higher than the ϕ_{I-V} values in the measured 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 [**5, 38**]. The capacitance C is insensitive to potential fluctuations on a length scale of less than the space-charge width and the C-V method averages over the whole area. The dc current I across the interface depends exponentially on ϕ_{bo} and thus sensitively the detailed barrier distribution at the interface. According to Werner and Guttler, spatial inhomogeneities at the metal/n-InP interface of abrupt Schottky contact can also cause such differences in the barrier height determined from I-V and C-V measurements.

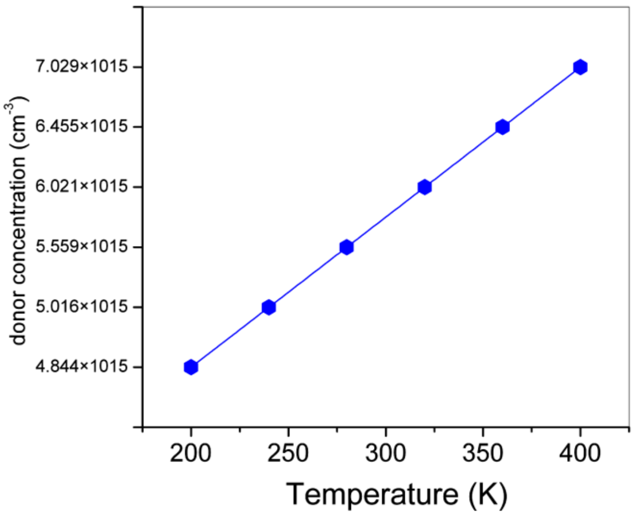

Fig. 8. The reverse bias C^{-2}-V characteristics of the Pd/V/n-InP Schottky diode at different temperatures in the range 200-400 K.

Several reasons have been reported in the literature such as surface contamination at the interface, deep impurity levels, an intervening insulator layer, quantum-mechanical tunneling, image-force lowering and edge leakage currents [**39**]. Any spatial variations in the barriers causes the current I to flow preferentially through the barrier minima. That is, the current in the I-V measurement is dominated by the current which flows through the region of low SBH. Since the low-SBH is pinched off, the effective SBH of the patch is the potential at the saddle point [**38**]. Consequently, for an inhomogeneous interface, the spatial variation of the band bending results in different BH for the current and capacitance and the capacitances are expected to measure only the mean BH value.

Determination of interface state density

There is always a deviation of the ideality factor at high currents that is clearly shown to depend on parameters such as, the interfacial layer thickness, the interface density and series resistance. For calculating barrier height and other characteristic parameters, the interface states play an important role at conducting metal/semiconductor rectifying contact. When the interfacial layer is sufficiently thick and the transmission probability between the metal and the interface states is very small. The effective barrier height ϕ_e is assumed to be bias-dependent due to the presence of an interfacial layer and interface states located at the between interfacial layer semiconductor interface and is given by [**40**]

$$\phi_e = \phi_{bo}^{I-V}\left(\frac{d\phi_e}{dV}\right) = \phi_{bo}^{I-V} + \beta V \tag{21}$$

where $\beta = 1-(1/n)$ is change in the effective barrier height with bias voltage.

For Pd/V/n-InP Schottky structure having interface states in equilibrium with the semiconductor, the ideality factor 'n' becomes greater than unity as proposed by Card and Rhoderick [**41**] and is given by

$$n(V) = 1 + \frac{\delta}{\varepsilon_i}\left[\frac{\varepsilon_S}{W_D} + qN_{SS}\right] \tag{22}$$

where W_D is the space charge region width, δ is the thickness of interfacial layer, ε_i and ε_s are the permittivities of the interfacial layer and the semiconductor and N_{SS} is the density of interface states, respectively. Thus, according to equation (22), the interface density can be given as

$$N_{SS}(V) = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V)-1) - \frac{\varepsilon_S}{W_D}\right] \tag{23}$$

Moreover, in an n-type semiconductor, the energy of the interface states E_{SS} with respect to the bottom of the conduction band edge at the surface of the semiconductor is given by [**41-43**]

$$E_C - E_{SS} = q(\Phi_e - V) \tag{24}$$

Equation (21)-(24), along with the I-V characteristics can be used for the determination of the interface states density as a function of interface states energy E_{SS} with respect to the bottom of the conduction band. Thus, using equations (23) and (24) by taking into account the bias dependence of the ideality factor n(V) and BH the energy distribution of the interface states in equilibrium with the semiconductor as a function of V is determined.

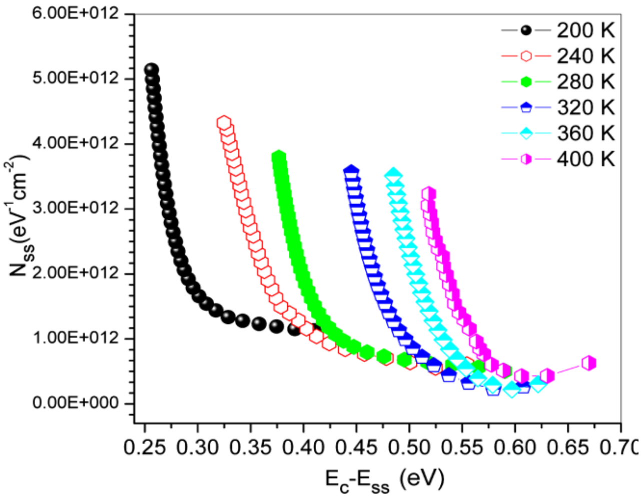

Fig. 9. Interface state density distribution profiles as a function of E_C-E_{SS} for the Pd/V/n-InP Schottky diodes at various temperatures.

Fig. 9 shows the curves of interface state density distribution determined from the downward curvature region of the experimental semilog forward bias I-V characteristics of the Pd/V/n-InP Schottky barrier diode in the temperature range of 200 K to 400 K. From **Fig. 9**, it can be seen that an exponential increase in interface states density exists from mid gap towards the bottom of the conduction band. The magnitude of the interface state density (N_{SS}) is varied from 5.14×10^{12} $eV^{-1}cm^{-2}$ (E_C-0.25 eV) to 1.13×10^{12} $eV^{-1}cm^{-2}$ (E_C-0.40 eV) at 200 K. Also, at 400 K, the magnitude of the interface state density (N_{SS}) is varied from $3.21\times10^{12}eV^{-1}cm^{-2}$ (E_C-0.51 eV) to 6.28×10^{11} $eV^{-1}cm^{-2}$ (E_C-0.66eV). Such behaviour of N_{SS} has been explained with variation of the ideality factor as a function of temperature due to lateral inhomogeneities of the barrier height at the metal-semiconductor interface [**44**]. In the determination of the Schottky barrier parameters of the devices the interface states and interfacial layer between the metal/semiconductor play an important role. These findings probably indicate that the Fermi level pinning is partially relieved so that the Fermi level moves relatively to the conduction band edge with the applied voltage upon the interlayer which modification of the interface.

Conclusion

The electrical transport mechanisms of Pd/V/n-InP SBDs have been investigated in the temperature range of 200-400 K. The basic diode parameters such as the ideality factor and BH are extracted from electrical measurements of Pd/V/n-InP Schottky rectifying contacts. The ideality factor seems to increase and BHs decrease with a decrease in temperature. These observations have been ascribed to barrier inhomogeneities at the metal-semiconductor interface. The inhomogeneities can be described by the Gaussian distribution of barrier heights with a mean barrier height $\bar{\phi}_{bo}$ = 0.89 eV and standard deviation σ_0 = 145 meV respectively. A modified $\ln\left(\frac{I_o}{T^2}\right)-\left(\frac{q^2\sigma_o^2}{2k^2T^2}\right)$ versus $10^3/T$ plot yielded zero-bias mean BH value of 0.72 eV and Richardson constant as 6.59 Acm^{-2}K^{-2} for n-InP is obtained considering Gaussian distribution of the barrier height. Furthermore, in the temperature range of 200-400 K, the experimental values of ideality factor are in agreement with characteristics energy of 20 meV. Therefore, we suggest that the current transport through the junction is also influenced by the TFE mechanism. 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.

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