J. Nano- Electron. Phys.
3 (2011) No1, P. 1048-1055

© 2011 SumDU
(Sumy State University)

PACS numbers: 73.30. + y, 73.40.Ei

ELECTRICAL TRANSPORT CHARACTERISTICS OF PD/V/N-INP SCHOTTKY DIODE FROM I-V-T AND C-V-T MEASUREMENTS

S. Sankar Naik, V. Rajagopal Reddy

Department of Physics, Sri Venkateswara University,
Tirupati-517502, India
E-mail: shankarnaik.phd@gmail.com

The temperature dependence of current-voltage (I-V) and capacitance-voltage (C-V) characteristics of the Pd/V *contacts on undoped n-type* InP *Schottky barrier diodes (SBDs) have been systematically investigated in the temperature range of* 200-400 *K. The transition metal palladium (*Pd*) is used as a second contact layer because it has high work function, it reacts with* InP *at low temperatures and improved contact morphology. The ideality factor (n) and zero-bias barrier height are found to be strongly temperature dependent and while the zero-bias barrier height Φ_{bo} (I-V) increases, the ideality factor n decreases with increasing temperature. The experimental values of BH and n for the devices are calculated as* 0.48 *eV (I-V),* 0.85 *eV (C-V) and* 4.87 *at* 200 *K,* 0.65 *eV (I-V),* 0.69 *(C-V) eV and* 1.58 *at* 400 *K respectively. The I-V characteristics are analyzed on the basis of thermionic emission (TE) theory and the assumption of Gaussian distribution of barrier heights due to barrier inhomogeneities that prevail at the metal-semiconductor interface. The zero-bias barrier height Φ_{bo} versus* 1/2*kT plot has been drawn to obtain the evidence of a Gaussian distribution of the heights and the values of $\bar{\varphi}_{b0} = 0.89$ eV and $\sigma_0 = 145$ meV for the mean barrier height and standard deviation. The conventional Richardson plot exhibits non-linearity with activation energy of* 0.53 *eV and the Richardson constant value of 4.25×10^{-6} Acm^{-2} K^{-2}. From the C-V characteristics, measured at* 1 *MHz the capacitance was determined to increase with increasing temperature. C-V measurements have resulted in higher barrier heights than those obtained from I-V measurements. As a result, it can be concluded that the temperature dependent characteristic parameters for* Pd/V/*n*-InP *SBDs can be successfully explained on the basis of TE mechanism with Gaussian distribution of the barrier heights.*

Keywords: *Pd / V SCHOTTKY CONTACTS; n-TYPE InP, TEMPERATURE DEPENDENT I-V AND C-V MEASUREMENTS, GAUSSIAN DISTRIBUTION; BARRIER INHOMOGENEITY.*

(Received 04 February 2011, in final form 30 November 2011)

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 play an crucial role in constructing some useful devices in technology [1-2]. Indium phosphide (InP) is an attractive III-V compound semiconductor which finds wide applications in opto-electronic and high-speed electric devices due to a direct bandgap and high electron mobility [3]. However, a serious draw back of InP is the low Schottky barrier height

(BH). This increases the leakage and the device performance is degraded. Schottky barrier diodes (SBDs) with low BH have found applications in devices operating at cryogenic temperatures as infrared detectors and sensors in thermal imaging [4]. Therefore, analysis of the I-V characteristics of the Schottky barrier diode (SBDs) at room temperature only does not give detailed information about their conduction process (or) the nature of barrier formation at the MS interface. The temperature dependence of the I-V characteristics allows us to understand different aspects of conduction mechanisms. However, a complete description of the charge carrier transport through an MS contact is still a challenging problem.

The efforts have been made to improve Schottky barrier heights by several research groups [5-7]. Ashok et al. [5] investigated Pd/Pt Schottky contacts on n-InP (100) in a wide temperature range (230-410 K) and they found a decrease of BH and increase of ideality factor with decreasing temperature. Shi and Andersson [6] studied the current transport in Pd/n-InP diodes formed at room and low temperatures. They reported that the barrier height and ideality factor are 0.48 eV and 1.02 for the RT diode, 0.96 eV and 1.16 for the LT diode. Recently Bhaskar Reddy et al. [7] evaluated the current-voltage-temperature (I-V-T) characteristics of Pd/Au Schottky contacts on n-InP (111). They found that the BH and ideality factor varied from 0.35 eV and 2.14 at 220 K to 0.57 eV and 1.42 at 400 K. In this work, vanadium (V) is selected as a first contact layer because of its low work function as well as to provide the lowest forward voltage drop. The near noble metal palladium (Pd) is used as a second contact layer because it reacts with InP during electron beam evaporation deposition [8] as well as enhances the barrier height [9]. In the present work, the current-voltage (I-V) and the capacitance-voltage (C-V) measurements of the Pd/V Schottky contacts on n-InP SBDs have been made over the temperature range 200-400 K.

2. EXPERIMENTAL DETAILS

Liquid Encapsulated Czochralski (LEC) grown undoped n-InP (111) samples with carrier concentration of 4.5×10^{15} cm^{-3} are used in the present work. The samples are initially degreased with organic solvents like trichloroethylene, acetone and methanol by means of ultrasonic agitation for 5 min in each step to remove the contaminants followed by rinsing in deionized (DI) water. The samples are then etched with HF (49 %) and H_2O (1:10) to remove the native oxide from the substrate. Indium is deposited with a thickness of 500 Å on the rough side of the InP wafer as ohmic contact prior to Schottky diode fabrication under a pressure of 7×10^{-6} mbar, which are then annealed at 350 °C for 1 min in nitrogen atmosphere. For making Schottky contacts, the metal Pd/V of 200 Å/300 Å thickness through a stainless steel mask of diameter 0.7 mm are deposited on the polished side of the InP wafer. The current-voltage (I-V) and the capacitance-voltage (C-V) measurements of Pd/V Schottky contacts are made using a SEMI LAB DLS-83D deep level spectrometer over the range of 200-400 K in steps of 40 K.

3. RESULTS AND DISCUSSION

The semi-logarithmic I-V characteristics of the Pd/V/n-InP SBDs in the temperature range of 200-400 K in steps of 40 K are shown in Fig. 1. From the thermionic emission theory, the current-voltage (I-V) relationship for Schottky barrier diode is given by expression [2]

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

where I_0 is the saturation current which is obtained from the intercept of $\ln(I)$ versus V plot, at $V = 0$, the ideality factor is obtained from the linear portion of the plot between the natural log of current and voltage. The calculated values of BH and ideality factor are varied from 0.48 eV and 4.87 at 200 K to 0.65 eV and 1.58 at 400 K respectively as shown in Fig. 2.

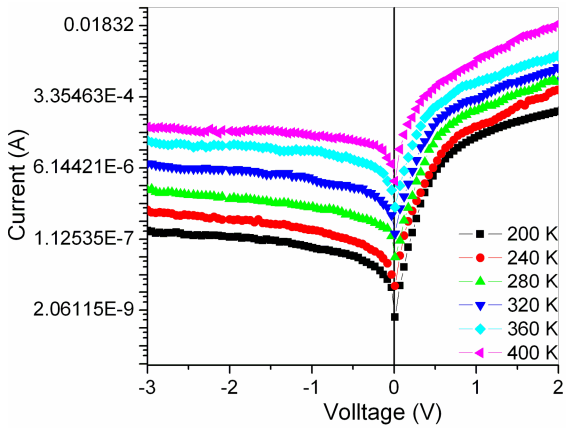

***Fig. 1** – Typical forward and reverse current-voltage (I-V) characteristics of* Pd/V *Schottky contact on n-type* InP *in the temperature range of* 200-400 *K*

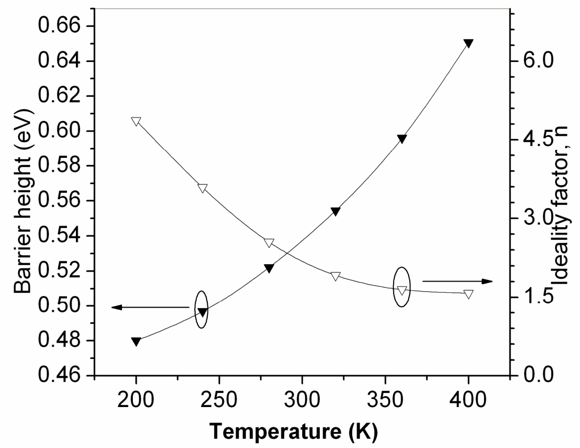

***Fig. 2** – Temperature dependence plot of barrier height and ideality factor in range of* 200-400 *K*

From Fig. 2 the ideality factor n exhibits a decreasing trend with increasing temperature, whereas the zero-bias barrier height Φ_{bo} shows increasing trend as temperature increases. Since the current transport across the metal-semiconductor 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 patches of the lower Schottky barrier height and a large ideality factor [10].

The experimental reverse bias C^{-2}-V characteristics of the Pd/V/n-InP Schottky diode over the temperature range 200-400 K are shown in Fig. 3. The junction capacitance has been measured at 1 MHz frequency. In Schottky contacts, the depletion layer capacitance is expressed as [11],

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

where V_{bi} is the flat band voltage, N_d the donor concentration, A the area of the Schottky contact and ε_s the permittivity of the semiconductor ($\varepsilon_s = \varepsilon_o$). The X-intercept of the plot of $(1/C^2)$ versus V gives V_0. V_0 is related to V_{bi} by the equation $V_{bi} = V_0 + kT/q$. The barrier height from C-V characteristics is given by the equation $\Phi_{cv} = V_{bi} + V_n$ where $V_n = (kT/q)\ln(N_c/N_d)$ The density of states in the conduction band edge is given by $N_c = 2\ (2\pi m^* kT/h^2)^{3/2}$, where $m^* = 0.078\ m_0$ and its value is 5.7×10^{17} cm^{-3} for InP at room temperature. Moreover, the temperature dependence of the experimental donor concentration (N_d) has been calculated from the slope of the reverse bias C^{-2}-V characteristic in Fig. 3. The values of N_d varied between 4.844×10^{15} cm^{-3} and 7.029×10^{15} cm^{-3} as the temperature varied between 200 and 400 K. It can be seen from Fig. 4, the donor concentration of the n-InP decreased with decrease in temperature. The temperature dependent N_c and N_d values are used in calculating Φ_{cv}. The barrier height values obtained from the reverse bias C^{-2}-V characteristics has varied from 0.85 eV to 0.69 eV in the temperature range 200-400 K. Due to the square dependence of Φ_{cv} on 1/C compared to the logarithmic dependence of Φ_{bo} on the current, Φ_{cv} is more sensitive to the experimental errors of the measured data than Φ_{bo} [12].

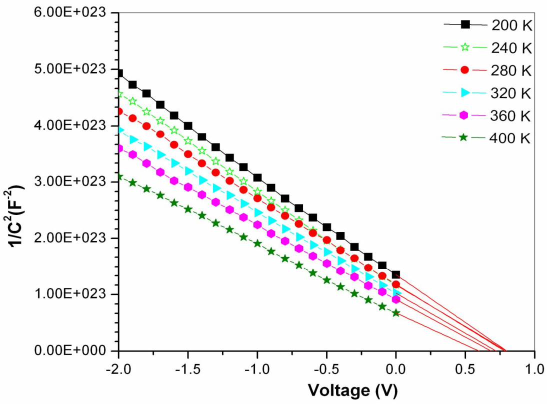

Fig. 3 – *The reverse bias C^{-2}-V characteristics of the Pd/V Schottky contact at different temperatures in the range 200-400 K*

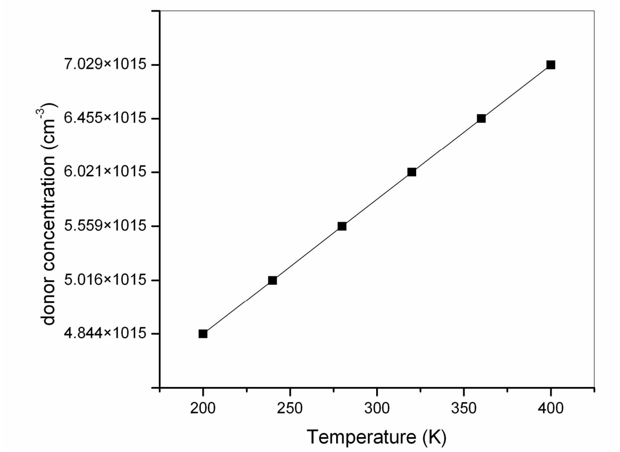

***Fig. 4** – Temperature dependence of the donor concentration from experimental reverse bias C^{-2}-V characteristics of* Pd/V *Schottky contact*

It is seen from Fig. 4, that the barrier height $\Phi_{(CV)}$ increases with decreasing temperature. The temperature dependence of $\Phi_{(CV)}$ is expressed as

$$\varphi_{(CV)} = \varphi_{(CV)}(T = 0) + \alpha T \tag{3}$$

where $\varphi_{(CV)}$ $(T = 0)$ is the barrier height extrapolated to zero temperature and α is the temperature coefficient of the barrier height. Fitting of the experimental data into equation (3) gives $\alpha = -4.28 \times 10^{-4}$ eV/K which is temperature coefficient of the InP bandgap [13] and $\varphi_{(CV)}$ $(T = 0)$ $\alpha = 0.81$ eV. The calculated φ_{IV}, ideality factor n, φ_{CV} and N_d values are shown in Table 1.

***Table 1** – Temperature dependent values of various parameters determined from I- V and C-V characteristics of Pd/V Schottky contact*

Temperature (K)	φ_{IV} (eV)	φ_{CV} (eV)	Donor concentration (N_d) cm $^{-3}$	Ideality factor, n
200 K	0.48	0.85	4.844×10^{15}	4.87
240 K	0.50	0.83	5.016×10^{15}	3.58
280 K	0.52	0.79	5.559×10^{15}	2.55
320 K	0.55	0.77	6.021×10^{15}	1.92
360 K	0.59	0.74	6.455×10^{15}	1.64
400 K	0.65	0.69	7.029×10^{15}	1.58

In order to explain the abnormal deviations of I-V characteristics of the Schottky diode from the classical thermionic emission theory, we adopted as lateral distribution of barrier height with a Gaussian distribution. The Gaussian distribution of the BH yields the following expression for the BH [11, 14] as,

$$\varphi_{bo} = \bar{\varphi}_{bo}(T=0)\frac{q\sigma_0^2}{2kT} \qquad (4)$$

where 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 [15],

$$\left(\frac{1}{n_{ap}} - 1\right) = -\rho_2 + \frac{q\rho_3}{2kT} \qquad (5)$$

where ρ_2 and ρ_3 quantify the voltage deformation coefficients of the barrier height distribution. The decrease of zero-bias barrier height may be caused by the existence of the Gaussian distribution and the extent of influence is determined by the standard deviation. Also, the effect is particularly significant at low temperatures. The experimental Φ_{bo} versus $1/T$ and n versus $1/T$ plots (Fig. 5) are drawn by means of the data obtained from Fig. 1. As can be seen in Fig. 5, the values of $\bar{\varphi}_{b0} = 0.89$ eV and $\sigma_0 = 145$ meV are obtained from the experimental φ_{bo} versus $1/T$ plot and in the same figure, 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, the values of $\rho_2 = -0.026$ and $\rho_3 = 0.076$ are obtained from this plot.

For the evaluation of barrier height, one may also make use of the Richardson plot of the saturation current Eq.(1) can be written as,

$$\ln\left(\frac{I_0}{T^2}\right) = \ln(AA^{**}) - \frac{q\varphi_{bo}}{kT} \qquad (6)$$

The plot of $\ln(I_0/T^2)$ versus 1000 / T is found to be non-linear in the measured temperature (shown in Fig. 6) and is caused by the temperature dependence of the barrier height and the ideality factor. An activation

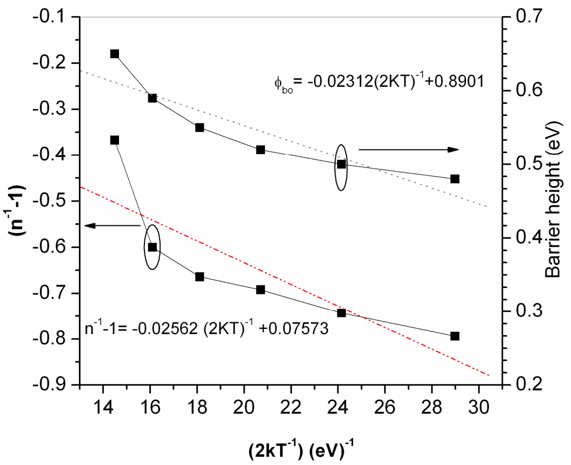

Fig. 5 – *The zero-bias barrier height and ideality factor versus $1/2kT$ curves of the Pd/V Schottky contact according to Gaussian distribution of barrier heights*

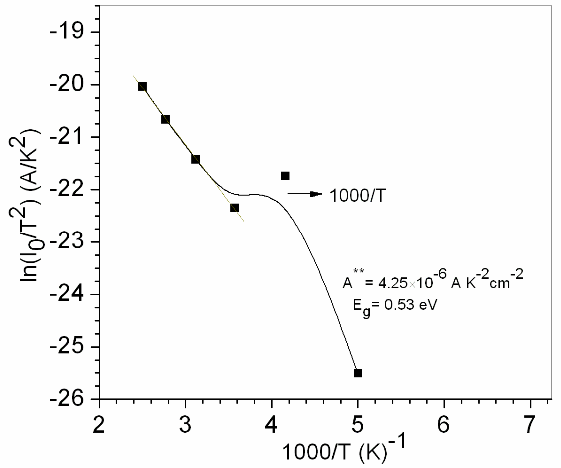

Fig. 6 *– Richardson plot of* $\ln(I_0/T^2)$ *versus* $10^3/T$ *for Pd/V Schottky contact*

energy value of 0.53 eV is obtained from the intercept of the straight line portion of device. The value of A^{**} obtained from the intercept of the straight portion of the ordinate and is equal to 4.25×10^{-6} Acm^{-2}K^{-2} which is lower than the known value of 9.4 Acm^{-2}K^{-2} for n-InP. The A^{**} value obtained from the temperature dependence I-V characteristics may be effected by lateral inhomogeneity on the barrier and the fact that it is different from theoretical value, may be content of a value of the real effective mass that is different from calculated one.

4. CONCLUSIONS

The current transport mechanism in Pd/V Schottky contact has been investigated by means of I-V and C-V measurements at various temperature range 200-400 K. It is found that the ideality factor n of the diode decreases while the corresponding zero-bias SBH increasing with an increase in temperature, have been successfully explained on the basis of TE theory with a Gaussian distribution of BHs at the interface. This behaviour is attributed to spatial variations of the BHs. The non-linearity in the Richardson plot gives a clear indication of the inhomogeneity in the barrier height. The extracted value of mean barrier height and standard deviation clearly indicates the presence of interface inhomogeneities and potential fluctuation at the interface.

REFERENCES

1. R.T. Tung, *Mater. Sci. Eng. R.* **35,** 1 (2001).
2. E.H. Rhoderick, R.H. Williams, *Metal-semiconductor contacts* (2nd edn Oxford Clarendon: 1988).
3. H.K. Henisch, *Semiconductor contacts* (Oxford University: London: 1984).
4. S. Chand, J. Kumar, *Appl. Phys. A* **63,** 171 (1996).
5. A. Ashok Kumar, V. Janardhanam, V. Rajagopal Reddy, P. Narasimha Reddy, *Superlattice Microst.* **45,** 22 (2009).
6. Z.Q. Shi, W.A. Andersson, *J. Appl. Phys.* **72,** 3803 (1992).

7. M. Bhaskar Reddy, A. Ashok Kumar, V. Janardhanam, V. Rajagopal Reddy, P. Narasimha Reddy, *Curr. Appl. Phys.* **9**, 972 (2009).
8. D.G. Ivey, L. Zhang, P. Jian, *J. Mater. Sci - Mater. El.* **2**, 21 (1991).
9. J.W. Palmer, W.A. Andersson, D.T. Hoelzer, M. Thomas, *J. Electron. Mater.* **25**, 1645 (1996).
10. R.T. Tung, *Phys. Rev. B* **45**, 13509 (1992).
11. S. Chand, S. Bala, *Appl. Surf. Sci.* **252**, 358 (2005).
12. S.Y. Zhu, R.L. Van Meirhaeghe, C. Detavernier, F. Cardon, G.P. Ru, X.P. Qu, B.Z. Li, *Solod-State Electron.* **44**, 663 (2000).
13. Y.S. Tsay, B. Gong, S.S. Mitra, J.F. Vetelino, *Phys. Rev. B* **6**, 2330 (1972).
14. Y.P. Song, R.L. Van Meirhaeghe, W.H. Laflere, F. Cardon, *Solid State Electron.* **29**, 633 (1986).
15. J.H. Werner, H.H. Guttler, *J. Appl. Phys.* **69**, 1522 (1991).