Temperature dependence of current-voltage characteristics of the Pd/InP Schottky contacts

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The temperature dependence of current-voltage characteristics of the Pd Schottky contacts on n-InP (100) has been measured in the temperature range of 200-400 K. Based on thermionic emission (TE) theory, the forward and reverse current-voltage (I-V) characteristics are analyzed to estimate the Schottky barrier parameters. It is observed the decrease in ideality factor and increase in barrier height (BH) with increasing temperature. The estimated values of barrier height and ideality factor are varied from 0.38 eV and 5.48 at 200 K to 0.7 eV and 2.01 at 400 K respectively. The calculated value of Richardson constant is 2.18 A cm^{-2} K^{-2} from temperature dependent I-V studies, which is lower than the known value. The nonlinearity in the Richardson plot and strong dependence of Schottky barrier parameters on temperature may be attributed to the spatial inhomogeneity in the interface. Potential fluctuation model has been used to explain the results obtained in this study.

1. Introduction

Metal-semiconductor structures are essential research tools in the characterization of new semiconductor materials. Indium phosphide (InP) is an attractive III-V compound semiconductor and is of considerable interest in opto-electronic applications and high speed electronic devices due to a direct transition bandgap and high electron mobility, both of which are very important in fabricating some useful devices in technology [1-4]. However, a serious drawback of InP Schottky barrier diodes (SBD) is the low barrier height (BH) and large leakage currents which may be due to Fermi level pinning. SBD with low barrier height have found applications in devices operating at cryogenic temperatures as infrared detectors and sensors in thermal imaging [5, 6].

The interface quality between the deposited metal and the semiconductor surface decides the performance and reliability of a SBD. The observed current-voltage (I-V) characteristics of the real SBD usually deviate from the ideal thermionic emission (TE) model. The strong dependence of both BH and ideality factor on temperature and the nonlinearity of the Richardson plots are the factors associated with the deviation of the TE model [7-10].

On the other hand, it is found that BH is inhomogeneous in the metal-semiconductor (M-S) interface. This is also one of the mechanism for deviating the I-V characteristics from the ideal TE model. The mechanisms responsible for producing an inhomogeneity are not yet fully understood. The BH is likely to be a function of the interface atomic structure and the inhomogeneity at a MS interface may be caused by grain boundaries, multiple phases, facets, defects, and a mixture of different phases [11-18]. The deviation in TE model observed in I-V characteristics could be quantitatively explained by assuming specific distribution of nanometer scale patches of small regions with low BH. In such cases, the current across the MS contact may be greatly influenced by the presence of interfacial patches [15-18].

Some authors observed the non-ideal behaviour of the SBD's which is accounted by certain distribution of microscopic barrier heights for the different diodes [19-21]. Tung and co-workers have modeled imperfect Schottky contacts by assuming lateral variations of the barrier height [17, 18]. Shi et al discussed on the temperature dependent current transport phenomena in Pd/InP MIS diodes [22, 23]. However, they have not proposed any inhomogeneity in the interface for the variations of the barrier height. According to their study the variations of the SBD parameters may be due to some interface states existed between metal and semiconductor. This was due to the passivation of the surface by some insulating material.

In the present work, we have investigated the temperature-dependence of I-V characteristics of Pd/InP Schottky diodes in the temperature range of 200-400 K. The current-voltage-temperature (I-V-T) measurements are used to explain the current transport mechanism and inhomogeneity in the barrier and to estimate the SBD parameters such as the barrier height and ideality factor as a function of temperature.

2. Experimental details

The samples used in this study are Czochralski grown undoped n-InP (100). The samples are initially cleaned with organic solvents trichloroethylene, acetone and methanol by means of thermal agitation for 5 min to remove contaminants. The cleaned samples are rinsed in deionized (DI) water and then dried in nitrogen ambient is followed by etching with HF (49%) and H_2O (1:10) to remove the native oxide. Ohmic contacts with thickness of

700 A^o are formed on the rough side of the InP sample under a vacuum of 7×10^{-6} mbar which are then annealed at 350 ^{o}C for 1 min in N$_2$ atmosphere. The samples are then placed in vacuum chamber for forming Pd Schottky contacts on the polished side of the InP through a metal mask of diameter 1 mm. The thickness of the metal contact is 500 A^o. The temperature dependent characteristics of the Pd/InP Schottky contacts have been carried out over the temperature range from 200-400 K. Further, the electrical measurements such as current – voltage characteristics were measured from DLS-83D spectrometer.

3. Results and discussion

Typical forward current-voltage characteristics of Pd/n-InP Schottky contacts in the temperature range of 200-400 K are shown in Fig. 1. The forward current according to the TE theory can be expressed as, [24]

$$I=I_o \exp\left[\frac{qV}{nkT}-1\right] \qquad (1)$$

where $\qquad I_o=AA^*T^2 \exp\left[\frac{q\phi_b}{kT}\right] \qquad (2)$

I_o is the reverse saturation current, q is the electron charge, V is the applied voltage, the ideality factor n is written as

$$n = \frac{q}{kT}\left[\frac{dV}{d(\ln I)}\right] \qquad (3)$$

A^* is the effective Richardson constant and ϕ_b is the Schottky barrier height. The value of barrier height (ϕ_b) can be deduced from the I-V curves with known value of Richardson constant A^*. The calculated value of A^* is 9.4 A cm^{-2} K^{-2} based on the effective mass (m*=0.08 m$_o$) of n-InP [25]. The reverse saturation current was determined from the intercept of a plot of I/[1-exp(-qV/kT)] versus V measured in the temperature range of 200 – 400 K is shown in Fig. 2. The calculated value of I$_o$ was used to determine the barrier height of the contacts. The ideality factor is obtained from the linear portions of the natural log of current versus voltage plot over the two orders of magnitude. Table 1 shows the reverse saturation current and barrier height of the Pd/InP schottky diode measured in the temperature range of 200-400 K. The value of the BH and ideality factor is changed from 0.38 eV and 5.48 at 200 K to 0.70 eV and 2.01 at 400 K respectively. Fig. 3 shows the variation of the BH with respect to temperature. It is observed the barrier height is increased linearly with increase in temperature from 200-400 K. Fig. 4 shows the plot of ideality factor obtained from Fig. 1 with respect to temperature. The increase in ideality factor is observed with decrease in temperature. Larger ideality factors are attributed to secondary mechanisms at the interface [1, 6-8, 17-19] such as lateral inhomogeneous distribution of barrier heights may be created by interface defects. The

barrier height of the Pd/InP Schottky contacts measured at room temperature is less than the ideal barrier height. This may be due to the Fermi level pinning caused due to the loss of phosphorous from the surface during alloying of the ohmic contact.   Then the deposited metal on the substrate may react with the In droplets formed on the surface which will make some interfacial compounds. These compounds may be responsible for decreasing the barrier height from the ideal values.
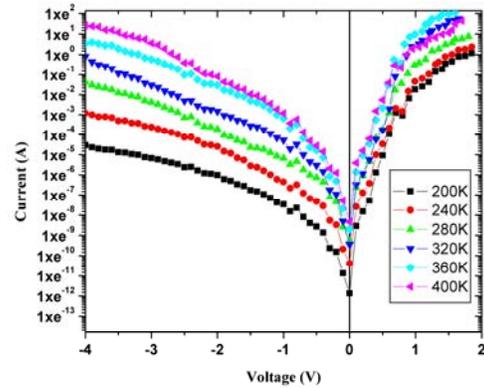

Fig. 1. Current-voltage characteristics of Pd/n-InP Schottky barrier diode as a function of temperature.

Table 1. Schottky barrier heights and ideality factor of the contacts as a function of sample temperature.

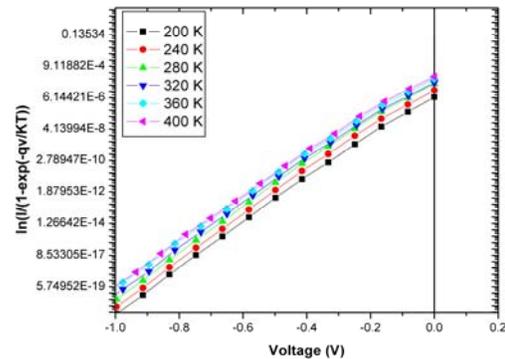| Sample temperature	Barrier height	Ideality factor
200 K	0.38 eV	5.48
240 K	0.44 eV	5.45
280 K	0.50 eV	4.05
320 K	0.57 eV	2.62
360 K	0.63 eV	2.27
400 K	0.70 eV	2.10

Fig. 2. Plot of I/[1-exp(-qV/kT)] versus V for the Pd contacts at different temperatures.
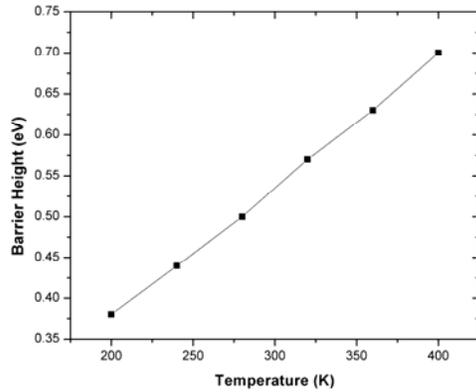
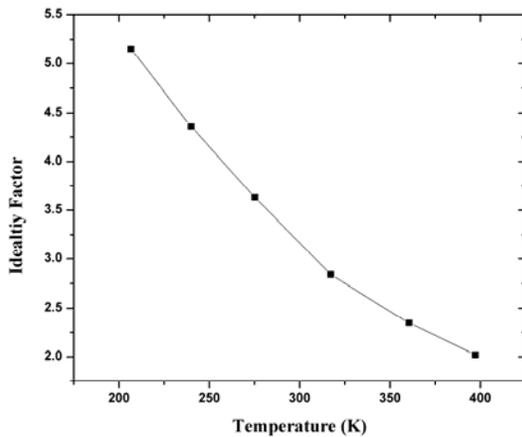*Fig. 3. Temperature dependence of zero-bias apparent barrier height for the Pd/InP Schottky contact.*

Fig. 4. Temperature dependence of the ideality factor for the Pd/InP Schottky contacts.

Low Schottky barrier heights and high ideality factors observed with decrease in temperature may be due to the discontinuities at the interface which are caused by grain boundaries, multiple phases, facets, defects, a mixture of different phases [11-18]. Many models have been evolved to explain the inhomogeneity in the barrier [1, 17, 18, 26-30]. Tung et al [3, 17] proposed a potential fluctuation model to explain the inhomogeneity in the barrier height which shows a larger deviation from the classical thermionic theory at low temperature than that predicted by other traditional models, such as image force lowering, an interfacial layer or interfacial states. The potential fluctuation model has been used to explain the temperature dependent results obtained for Pd/InP Schottky contacts. Due to the inhomogeneity, charge transport across the interface is no longer due to thermionic emission because of containing nanometer scale interfacial patches of small regions with low barrier heights imbedded in a higher background uniform barrier [17, 18, 31, 32]. Since current transport across the interface is temperature-activated process, electrons are able to overcome in the low barriers, and current transport will be dominated by current flowing

through the patches of lower barrier height and large ideality factor. According to potential fluctuation model, at sufficiently low temperatures, a large number of patches will be characterized and consequently, the current will be dominated by the flow of these patches. As the temperature increases, more and more electrons have sufficient energy to overcome the high barriers. As a result both the barrier height and ideality factor observed from temperature dependent   I-V characteristics are consistent with SBH inhomogeneity.

The Richardson plot shown in Fig. 5 is drawn between ln (I_o/T^2) versus 1000/T which is used to obtain the barrier height and Richardson constant. From equation 2, we can rewritten as,

$$\ln\left(\frac{I_O}{T^2}\right) = \ln(AA^*) - \frac{q\,\phi_b}{kT} \qquad (4)$$

The reverse saturation current I_o values obtained from the Fig. 2 is used in the Richardson plot. According to equation 4, the plot ln (I_o/T^2) yields a straight line with a slope given by barrier height at 0 K and the intercept is the Richardson constant. The experimental data are seen to fit asymptotically to a straight line at higher temperature only. However, for T>320 K the experimental points lie on a straight line. The value of A^* obtained from the intercept of the straight line portion of the ordinate is equal to 2.18 A cm^{-2} K^{-2}, which is lower than the known value of 9.4 A^{-2} cm^{-2} K^{-2}. A barrier height value of 0.2 eV is obtained from the slope of the straight line. The bowing of the experimental ln (I_o/T^2) versus 1/T plot is caused by the temperature dependence of the BH. The decrease in the barrier height and increase in the ideality factor with a decrease in temperature is evidenced from the I-V characteristics (Fig. 1). The decrease in barrier height at low temperatures leads to nonlinearity in the activation energy ln (I_o/T^2) versus 1/T plot. The deviation in the Richardson plot may be due to spatially inhomogeneous barrier height and potential fluctuation at the interface that consists of low and high barrier areas [17, 18] that is, the current through the diode will flow preferentially through the low barrier in the potential distribution. The results obtained in this work are consistent with the potential fluctuation model.
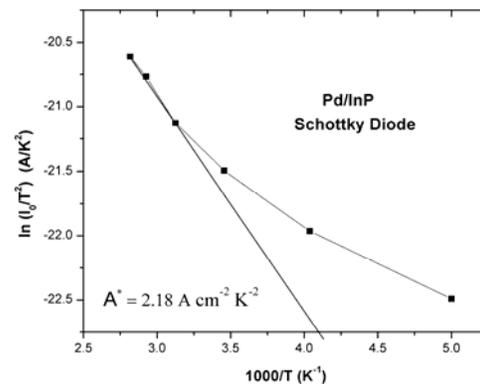

Fig. 5. Richardson plot of ln(I_o/T^2) vs. 10^3/T for the Pd/InP Schottky contacts.

4. Conclusion

We have investigated the temperature-dependent I-V characteristics of the Pd/InP Schottky diodes in the temperature range of 200-400 K. Based on the TE theory, the I-V characteristics of the Pd/InP (100) Schottky diode have been explained. The obtained I-V barrier heights are in the range of 0.38-0.70 eV with ideality factor of 5.48-2.10. The calculated ideality factor and barrier height shows strong dependence on temperature. The increase in ideality factor and decrease in barrier height with decrease in temperature may be attributed to spatial variations of the barrier height at the interface. The nonlinearity in the Richardson plot gives a clear indication of the inhomogeneity in the BH. The Richardson constant measured from temperature dependent I-V characteristics is 2.18 A cm^{-2} K^{-2} which is lower than the ideal value. The inhomogeneity in the BH is explained on the basis of potential fluctuation model.

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