Temperature dependent behavior of Sn/p-InP Schottky barrier diodes

D. KORUCU[*], Ş. ALTINDAL, T. S. MAMMADOV[a], S. ÖZÇELIK

Physics Department, Faculty of Arts and Sciences, Gazi University, 06500, Ankara, Turkey
[a]National Academy of Science, Institute of Physics, Baku, Azerbaijan

The observed non-ideal of Sn/p-InP Schottky barrier diode (SBD) parameters such as the zero-bias barrier height Φ_{Bo}(I-V) and ideality factor n were obtained from the forward bias current-voltage *(I-V)* characteristics in the temperature range of 80-400 K. By using the thermionic emission (TE) mechanism, the Φ_{Bo}(I-V) and n were found strongly temperature dependent and while the Φ_{Bo}(I-V) increases, the n decreases with increasing temperature. Also, especially at low temperatures the conventional Richardson plot is clearly non-linear. Such behavior of Φ_{Bo}(I-V) and n is attributed to SB inhomogeneities by assuming a Gaussian distribution (GD) of barrier heights (BHs) at metal/semiconductor interface. Therefore, $\overline{\Phi}_{Bo}$ and effective Richardson constant A^* are found as 1.151 eV and 56.954 A/cm^{2}K^2, respectively, from a modified $ln(I_o/T^2)-q^2\sigma_o^2/2(kT)^2$ *vs q/kT* plot and this value of the A^* (56.954 A/cm^{2}K^2) is very close to the theoretical value of 60 A/cm^{2}K^2 for p-InP.

1. Introduction

InP and its alloys have received increased attention in recent years due to their applications in metal-semiconductor (MS), metal-insulator-semiconductor (MIS), MIS field effect transistor (MISFET) devices, light emitting diodes (LEDs) and solar cells [1-9]. Only at room temperature, the forward bias *I-V* characteristics can not give us detail information about the current-transport mechanism. However, the temperature dependence of the *I-V* characteristics at wide temperature range allows us to understand different aspects of CTM. The current transport is dependent on various parameters such as surface preparation processes, inhomogeneity of the barrier height at M/S and insulator layer thickness at the M/S interface, density of interface states at insulator/semiconductor interface, series resistance of device and impurity concentration of semiconductor.

According to TE theory, the value of n is expected to be close to unity. However, the obtained value of ideality factor is greater than unity especially at low temperatures and this behavior of n can be attributed to the existence of insulator layer at M/S interface, particular distribution of interface states at semiconductor band-gap and the image force lowering of the barrier [10-16]. In this study, analysis of the *I-V* data of fabricated SBDs based on TE theory also reveals an abnormal decrease in the Φ_{Bo} and an increase in the n with a decrease in temperature. Similar results have been obtained in literature [6,10-18]. Such behavior of Φ_{Bo} at low temperatures leads to nonlinearity

in the activation energy $ln(I_o/T^2)$ *vs 1/T* plot. The nature and origin of the increase in the BH and decrease in the n with an increase in temperature in some studies have been successfully explained on the basis of the TE theory with a GD of the BHs [10-18].

In this study, the experimental *I-V* measurements revealed an increase of Φ_{Bo} but a decrease of n with increasing temperature. The temperature dependence of SBHs characteristics of Sn/p-InP SBDs were interpreted on the basis of the existence of GD of the BHs around a mean value due to barrier height inhomogeneities prevailing at the M/S interface.

2. Experiment details

Sn/p-InP SBDs were fabricated on the p-type (Zn doped) single crystal InP having thickness of 350 μm with 4-8x10^{17} cm^{-3} carrier concentration given by the manufacturer. The details of the cleaning procedure of the sample have been reported before [19]. The back side of the p-type InP was formed by sequentially evaporating Zn and Au layers on InP in a vacuum-coating unit of 10^{-6} Torr. After that, low resistance ohmic contact InP wafer was formed by sintering the evaporated Zn and Au layers at 350 °C for 3 min in flowing N$_2$ in a quartz tube furnace.

Finally, the Schottky contacts were formed by evaporating Sn dots with diameter of about 1mm on the front surface of the p-InP. The *I-V* characteristics of Sn/p-InP SBDs were performed by using a Keithley 2400

Sourcemeter and Janes vpf-475 cryostat in the temperature range of 80-400 K.

3. Results and discussions

The forward bias current- voltage *(I-V)* relation according to TE theory *(V>3kT/q)*, for a Schottky barrier diodes (SBD)s with the series resistance can be written as follows when [9]

$$I = I_o \exp\left(\frac{q(V - IRs)}{nkT}\right) x\,[\,1 - \exp\left(-\frac{q(V - IRs)}{kT}\right)\,] \tag{1}$$

where, V is the voltage applied across the diode, T is the absolute temperature in K, R_s is the series resistance of diode, n is the ideality factor and I_o is the reverse saturation current derived from the linear region of the intercept of *LnI vs V* at zero bias and can be expressed as

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

where A is the rectifier contact area of the diode, A^* is the effective Richardson constant of 60 A/cm^{-2}K^{-2} for p-type InP [20] and Φ_{Bo} is the zero bias BH of the diode and their values were calculated from Eq.(2). The value of n is calculated from the slope of the linear region as

$$n = \frac{q}{kT}\left(\frac{dV}{dLnI}\right) \tag{3}$$

Fig.1. shows the *LnI-V* characteristics of the Sn/p-InP SBD at various temperatures. The values of Φ_{Bo} and were calculated from Eq.(2) and Eq.(3), respectively, and shown in Table 1.

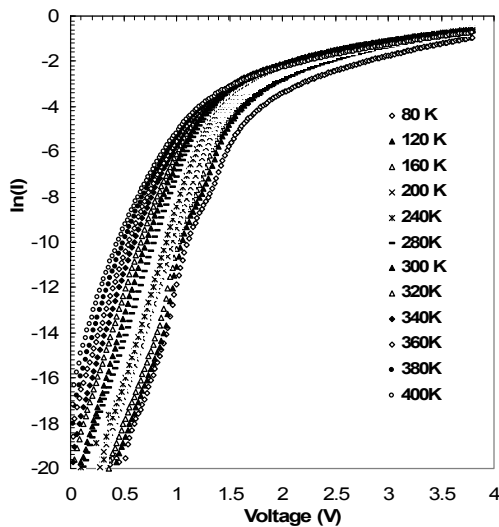*Fig. 1. The lnI-V characteristics of the Sn/p-InP SBD at various temperatures.*

Table 1. Temperature dependent values of various parameters for Sn/p-InP SBD.

T(K)	I_o(A)	n	Φ_{Bo}(eV)
80	6.01 x10^{-12}	11.239	0.234
120	1.35 x10^{-11}	7.766	0.350
160	2.41 x10^{-11}	5.666	0.467
200	4.09 x10^{-11}	4.056	0.582
240	8.00 x10^{-11}	3.261	0.693
280	3.60 x10^{-10}	2.908	0.779
300	7.00 x10^{-10}	2.401	0.821
320	2.60 x10^{-09}	2.446	0.843
340	4.91 x10^{-09}	2.191	0.881
360	1.60 x10^{-08}	2.185	0.899
380	2.96 x10^{-08}	2.022	0.933
400	9.06 x10^{-08}	1.992	0.947

As shown in Table 1, the values of Φ_{Bo} and n for the Sn/p-InP SBD ranged from 0.234 eV and 11.239(at 80 K) to 0.947 eV and 1.992 (at 400 K), respectively. Such behavior of n was attributed to the existence of a thick insulator layer at M/S interface and to particular distribution of interface states [9,15,21]. The value of n greater than unity are also attiributed to secondary mechanisms at the interface [22] As explained in refs. [10,15,23], since the current conduction across the metal/semiconductor interface is a temperature-activated process carriers at low temperatures are able to surmount the lower barriers. Therefore the current conduction will be dominated by the current following through the patches of lower SBH [10,13,17]. As can be seen in Table 1, the values of the ideality factor are higher than unity for each temperature and increase with decreasing temperature. The high values of the ideality factor show that there is a deviation from TE theory in the CTM.

A. The analysis of the inhomogeneous barrier and modified Richardson plot

By taking the natural logarithm of Equation (2), can be rewritten as and the *Ln(I$_o$/T^2) vs 1/T or 1/nT* plots

$$\ln\left(\frac{I_0}{T^2}\right) = \ln(AA^*) - \frac{q\Phi_{Bo}}{kT} \tag{4}$$

are given in Fig. 2. As shown in Fig. 2, the *Ln(I$_o$/T^2) vs 1/T* plot is found to be non-linear at low temperatures ($T \leq$ 200 K). However, the dependence of *Ln(I$_o$/T^2) vs 1/nT* is linear in the all measured .range. The deviation in the conventional Richardson plots may be due to the spatial inhomogeneous BH and potential fluctuations at the interface that consist of low and high barrier areas. When the experimental data are fitted between the temperature range of 240-400 K in Fig. 2 asymptotically with a straight line, it yields activation energy of 0.312 eV. Likewise, a A* value of 8.16x10^{-8} A cm^{-2} K^{-2} for the Sn/p-InP SBD was determined from the intercept at the ordinate of the

Ln(I_o/T^2) vs 1/T plot. This value of the A* is much lower then the known value of 60 A cm^{-2} K^{-2} for holes. Horvath [23] explained that the A* value may be affected by the lateral inhomogeneity of the barrier.

These abnormal behaviors can be explained by GD of BH with a mean value $\overline{\Phi}_{Bo}$ and standard deviation σ_o. The GD of the BHs yields the following expression of the BH as [1,11,12,23]

$$\Phi_{ap} = \overline{\Phi}_{B0}(T=0) - \frac{q\sigma_o^2}{2kT} \qquad (5)$$

where the temperature dependence of σ_o is usually small and can neglected[10,15,24]. The observed variation of ideality factor with temperature in the model is given by [11-16]

$$\left(\frac{1}{n_{ap}} - 1\right) = \rho_2 - \frac{q\rho_3}{2kT} \qquad (6)$$

where n_{ap} is apparent ideality factor and ρ_2 and ρ_3 are voltage coefficients which may depend on temperature, quantifying the voltage deformation of the BH distribution [14,25]. We was drawn a Φ_{Bo} *vs q/2kT* plot to obtain evidence of a GD [10-16] of BHs. Thus, the plot of Φ_{ap} vs *q/2kT* (Fig.3) should be a straight line that with the intercept at the ordinate determining the zero-bias mean BH $\overline{\Phi}_{Bo}$ (T=0) =1.182 eV and a slope giving the standard deviation σ_O = 132 mV. It was seen that the value of σ_O = 132 mV is not small compared to the mean value of $\overline{\Phi}_{Bo}$ =1.182 eV, indicating the presence of the interface inhomogenetes. The temperature dependence of *n* can be understood on the basis of Eq. (6). Similarly, as can be seen from Fig. 3, the value of ρ_2 obtained from the intercept of the experimental n_{ap} vs *q/2kT* plot is -0.2945 and the value of ρ_3 from the slope is - 154 mV.

The linear behavior of n_{ap} vs *q/2kT* plot demonstrates that the ideality factor indeed express the voltage deformation of the GD of the SBH. According to above results, this inhomogeneity and potential fluctuation dramatically affect especially low temperature *I-V* characteristics. It is responsible, in particular, for the curved behavior in the Richardson plot in Fig.2 [12,15,19,24]. As can be seen in Fig. 2, the plot of $\ln(I_o/T^2)$ versus 1/T plot shows that the activation energy which deviates from linearity under 200 K. In order to explain this behavior, according to GD of the BH, the modified Richardson plot can be rewritten as

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2\sigma_o^2}{2k^2T^2}\right) = \ln(AA^*) - \frac{q\overline{\Phi}_{B0}}{kT} \qquad (7)$$

A modified *ln(I_o/T^2)-q^2σ_O^2/2k^2T^2 vs q/kT* plot according to Eq.(7) should give a straight line with the slope directly yielding the mean barrier height $\overline{\Phi}_{B0}$ and the intercept (=lnAA^*) at the ordinate determining A* for a
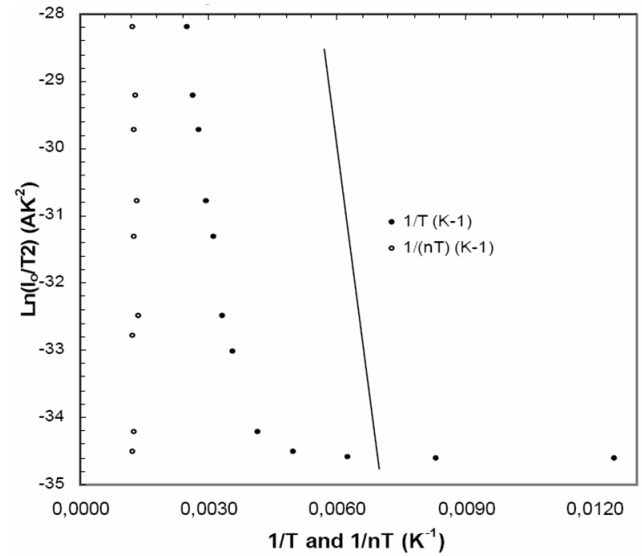

Fig. 2. Richardson plots of the ln(Io/T^2) vs 1/T or 1/nT for Sn/p-InP SBD.

given diode area A. In Fig.4, the modified $\ln(I_0/T^2)$-q$^2\sigma_o^2$/2k^{2}T^2 vs q/kT plot gives $\overline{\Phi}_{B0}$ (T=0) and A* as 1.151 eV and 56.95 A cm^{-2} K^{-2}, respectively, without using the temperature coefficient of the BHs. Interestingly, the value of A* is in reasonable agreement with the theoretical value of value of 60 A cm^{-2} K^{-2} for holes. Also, the value of $\overline{\Phi}_{B0}$ =1.151 eV from this plot is in close agreement with the value of $\overline{\Phi}_{B0}$ =1.182 eV from the plot of Φ_{ap} vs q/2kT. Hence, it has been concluded that the forward bias *I-V* characteristics of Sn/p-InP SBDs can be successfully explained on the basis of TE theory with a GD of the BHs.
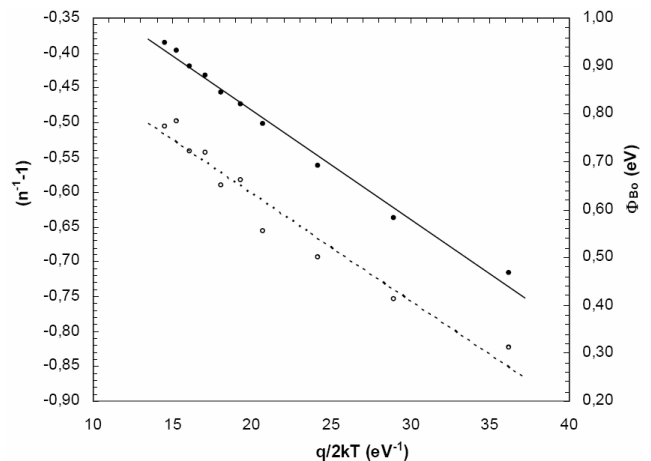

Fig. 3. The zero-bias apparent barrier height Φ_{Bo} (I-V) and thee ideality factor (n^{-1}-1) vs q/2kT plots for Sn/p-InP Schottky barrier diode according to Gaussian distribution of barrier heights.
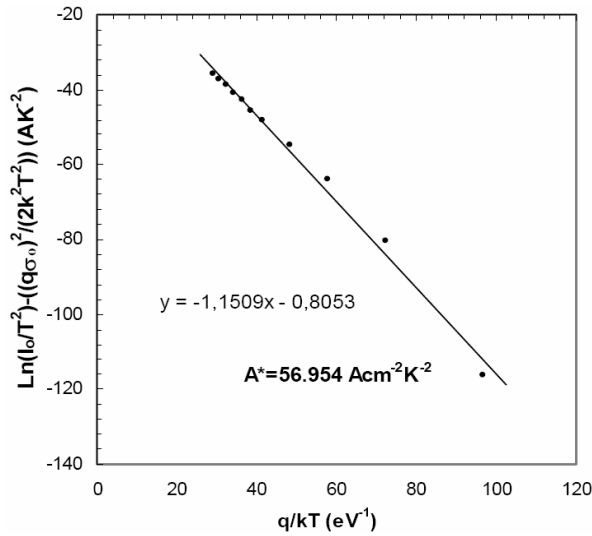
Fig. 4. Temperature dependence of $ln(I_o/T^2)-((q\sigma_o)^2/(2k^2 T^2))$ vs q/kT for Sn/p-InP SBD.

4. Conclusions

The forward bias *I-V* characteristics of the Sn/p-InP SBDwas measured in the temperature range of 80-400 K. By using the TE mechanism, the values of $\Phi_{Bo}(I\text{-}V)$ and n were found strongly temperature dependent and while the $\Phi_{Bo}(I\text{-}V)$ increases, the n decreases with increasing temperature. Such temperature dependence of $\Phi_{Bo}(I\text{-}V)$ is an obvious disagreement with the reported negative temperature coefficient of the BH and are attributed to SB inhomogenities by assuming a GD of BHs due to barrier inhomogeneties that prevails at M/S interface. Therefore, we attempted to draw a Φ_{Bo} vs $q/2kT$ plot to obtain evidence of a GS of the BHs , and the values of $\bar{\Phi}_{Bo}$=1.182 eV and σ_o=132 mV for the $\bar{\Phi}_B$ and standard deviation at zero bias, respectively, have been obtained from this plot. Thus, a modified $ln(I_o/T^2)-q^2\sigma_o^2/2(kT)^2$ vs q/kT plot gives $\bar{\Phi}_{Bo}$ and Richardson constant A^* as 1.151 eV and 56.954 A/cm²K², respectively, without using the temperature coefficient of the barrier height. This value of the Richardson constant 56.954 A/cm²K² is very close to the theoretical value of 60 A/cm²K² for p-InP. Hence, it has been concluded that the temperature dependence of the forward *I-V* characteristics of the Sn/p-InP SBDs can be successfully explained on the basis of TE mechanism with a GD of the BHs..

References

[1] Y. P. Song, R. L. Van Meirhaeghe, W. H. Laflere, F. Cardon, Solid-State Electron. **29,** 663 (1986).
[2] V. W. L. Chin, M. A. Green, J. W. V. Storey, J. Appl. Phys. **68,** 3470 (1990).
[3] A. Ahaitouf, A. Bath, E. Losson, E. Abarkan, Mater. Sci. and Eng.**B52,** 208 (1998).
[4] T. S. Huang, R. S. Fang, Solid State Electron. **37,** 1661 (1994).
[5] H. Çetin, E. Ayyildiz, Appl. Surf. Sci. **253,**) 5961 (2007).
[6] S. Asubay, Ö. Güllü, A. Türüt, Appl. Surf. Sci. xxx (2008) xxx (accepted).
[7] I. K. Han, J. Her, Y.T. Byun, S. Lee, D.H. Woo, J. I. Lee, Jpn. J. Appl. Phys. **33,** 6454 (1994).
[8] M. Yamaguchi, A. Khan, N. Dharmarasu, Solar Energy Materials & Solar Cells. **75,** 285 (2003).
[9] S. M. Sze, Physics Semiconductor Devices, John Wiley and Sons, New York, 1981.
[10] Ş. Karataş, Ş. Altındal, A Türüt, A. Özmen, Appl. Surf. Sci. **217,** 250 (2003).
[11] J. H. Werner, H. H. Güttler, J. Appl.Phys. **69,** 1522 (1991).
[12] S. Chand, S. Bala, Appl. Surf. Sci. **252,** 358 (2005).
[13] R. T. Tung, Phys. Rev. **B 45,** 13509 (1992).
[14] J. P. Sullivan, R. T. Tung, M. R. Pinto, W. R. Graham, J. Appl. Phys. **70,** 7403 (1991).
[15] S. Zeyrek, Ş. Altındal, H. Yüzer, M. M. Bülbül, Appl. Surf. Sci. **252,** 2999 (2006).
[16] S. Chand, J. Kumar, Semicond. Sci. Technol. **11,** 1203 (1996).
[17] A. Bengi, Ş. Altındal, S. Özçelik, T. S. Mammadov, Physica **B396,** 22 (2007).
[18] İ. Dökme, Ş. Altındal, İ. M. Afendiyeva, Semicond. Sci. Technol. **23,** 035003 (2008).
[19] D. Korucu, Ş. Altindal, T. S. Mammadov, S. Özçelik, Optoelectron. Adv. Mater. – Rapid Com. **2**(9), 525 (2008).
[20] E. Hökelek, G. Y. Robinson, Solid-State Electron. **99,** 24 (1981).
[21] Ş. Altındal, İ. Dökme, M. M. Bülbül, N. Yalçın, T. Serin, Microelectron. Eng. **83,** 499 (2006).
[22] W. Mönch, J. Vac. Sci. Tech. **B17,** 1867 (1999).
[23] Zs. J. Horvarth, Solid-State Electron. **39,** 176 (1996).
[24] M. K. Hudait, P. Venkateswarlu, S. B. Krupanidhi, Solid-State Electron. **45,** 133 (2001).
[25] S. Zhu, R. L. Van Meirhaeghe, C. Detavernier, F. Cardon, G. P. Ru, X.P. Qu, B. Z. Li, Solid-State Electron. **44,** 663 (2000).

_____
*Corresponding author: dkorucu@yahoo.com