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THE ROLE OF SERIES RESISTANCE ON THE FORWARD BIAS CURRENT-VOLTAGE (*I-V*) CHARACTERISTICS IN Sn/p-InP (MS) CONTACTS

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The forward bias current-voltage (*I–V)* characteristics of Sn/p-InP (MS) contacts are studied over a wide temperature range of 80-400 K. The effects of series resistance (R_s) and hole-tunneling factor on *I-V* characteristics are investigated. The R_s is significant in the downward curvature at high forward bias region. The values of ideality factor (n) and zero-bias barrier height (Φ_{Bo}) obtained from I-V-T measurements were strongly temperature dependent. While the value of n decreases with increasing temperature, Φ_{Bo} increases with increasing temperature. Also, the value of R_s gives a peak about room temperature. Such behaviors of n and Φ_{Bo} have been attributed to distribution of interface states (N_{ss}), inhomogeneity a native interfacial insulator layer and barrier height (BH). However, the effective BH (Φ_{Beff}) calculated from modified saturation current is decreased with increasing temperature according to literature.

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1. Introduction

Indium phosphide (InP) and the other related materials such as InGaP and InGaAsP are useful materials for the fabrication of opto-electronics, metal-semiconductor Schottky barrier diodes (SBDs) and high-frequency microwave devices [1-6]. Also, InP is important material for the fabrication of solar cells for space applications due to the high conversion efficiency and radiation resistance [7-9]. In particular, junction field-effect transistors (JFETs) in InP have excellent characteristics for high power and high-speed application [10]. Due to the importance of the performance and reliability of Schottky barrier diodes in the electronic industry, their electrical characteristics of SBDs have been extensively studied for over five decades [1-18].

In generally, main electrical parameters such as SBH, ideality factor (n), series resistance (R_s) and interface states (N_{ss}) are the most important parameters of the Schottky barrier diodes (SBDs) and especially change with temperature and bias voltage. Therefore, In this study, the forward bias current-voltage (*I–V)* characteristics of Sn/p-InP (MS) contacts are studied over a wide temperature range of 80-400 K. The effects of series resistance (R_s) and tunneling factor on *I-V* characteristics are investigated.

2. Experiment details

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The metal-semiconductor (Sn/p-InP) Schottky barrier diodes (SBDs) were fabricated on p-type (Zn doped) single InP crystal having (100) float zone, 350 μm thickness, 2" diameter and 4-8x10^{17} cm^{-3} doping concentration. Firstly, the p-InP wafer was cleaned with a 5 H_2SO_4+H_20_2+ H_20 solution for 1.0 min to remove surface damage layer and undesirable impurities and then in H_20+HCl solution, after that rinsed in de-ionized water with a resistivity of 18 MΩ cm. The wafer was dried with high purity nitrogen and inserted into the deposition chamber immediately after the etching process. 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. Therefore, low resistance ohmic contact InP wafer was formed by sintering the evaporated Zn and Au layers at 350 ^oC 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 current-voltage *(I-V)* characteristics of Sn/p-InP SBDs were performed by using a Keithley 2400 Sourcemeter in the temperature range of 80-400 K using a temperature controlled Janes vpf-475 cryostat. The bias voltage is swept from 0 to +4 V with 20 mV steps. Also, the sample temperature was always monitored by use of a copper-constant thermocouple close to the sample and measured with a Keithley model 199 DMM/scanner and Lake Shore model 321 auto-tuning temperature controllers.

3. Experimental results

When a SBD with series resistance is considered, the current through the junction can be given by the thermoionic emission (TE) theory for the relationship between the forward bias voltage *(V≥3kT/q)* and the current *(I)* of SBDs can be expressed as [19,20]

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

where I_o is the reverse saturation current and described by

$$I_o = AA^* T^2 \exp(-\chi^{0.5}\delta)\exp[-q\Phi_{bo} / kT] \tag{2}$$

is reverse saturation current, Φ_{bo} is the effective barrier height at zero bias, A is the diode area, A^* is the effective Richardson constant and equals to 60 A/cm^2K^2 for *p*-type InP [21], n is an ideality factor, χ is the mean barrier height presented by the thin interfacial insulator layer of thickness (δ), R_s is the series resistance of diode, T is the absolute temperature in Kelvin and V is the applied voltage.

Fig. 1 shows the wide temperature experimental forward bias *I-V* characteristics of Sn/p-InP SBDs. Using Eq. (1), the values of ideality factor n for each the Schottky diode were calculated from the slopes of the linear regions of the semi-log forward bias *I-V* plots, since the effect of series resistance in these linear regions is not significant. The values of ideality factor ranged from 11.239 to 2.022. Ours results clearly show that the SBDs ideality factors are considerably larger than unity. The high values of ideality factor can be attributed to the presence of a wide distribution of low-Schottky barrier height patches. The values of reverse saturation current (I_o) was obtained by extrapolating the linear intermediate bias regions (0.1≤V≤0.7) of the curve to zero applied voltage and the zero bias SBH Φ_{bo} values were calculated from Eq. (2). Here the oxide tunneling probability ($\chi^{0.5}\delta$) of the holes was assumed to be unity. The values of Schottky barrier height ranged from 0.947 to 0.234 eV. We can see in Table 1 that SBH values become smaller as the ideality factor values increase.

As shown in Fig. 1, the experimental semi-log forward bias *I-V* characteristics are linear in intermediate bias regions (0.1≤V≤0.7) 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 (V ≥ 0.7). The series resistance R_s is significant in the downward curvature (non-linear region) of the forward bias *I-V* characteristics, but the other two parameters are significant in both the linear and non-linear regions of the *I-V* characteristics. In Eq. (1), the term IR_s is the voltage drop across series resistance of Schottky diode. The voltage $V_d=V-IR_s$ across the Schottky diode can be expressed in terms of the total voltage drop *V* across the series combination of the Schottky diode and the series resistance. As the linear range of the forward *I-V* plots is reduced, the accuracy of the determination of Φ_{bo} and *n* becomes poorer. Therefore, the ideality factor, the series resistance, and barrier height were calculated using a method developed by Cheung functions [22] from data of downward curvature region (non-linear region) in the forward bias *I-V* characteristics:

$$\frac{dV}{d(LnI)} = n\frac{kT}{q} + IRs \tag{3}$$

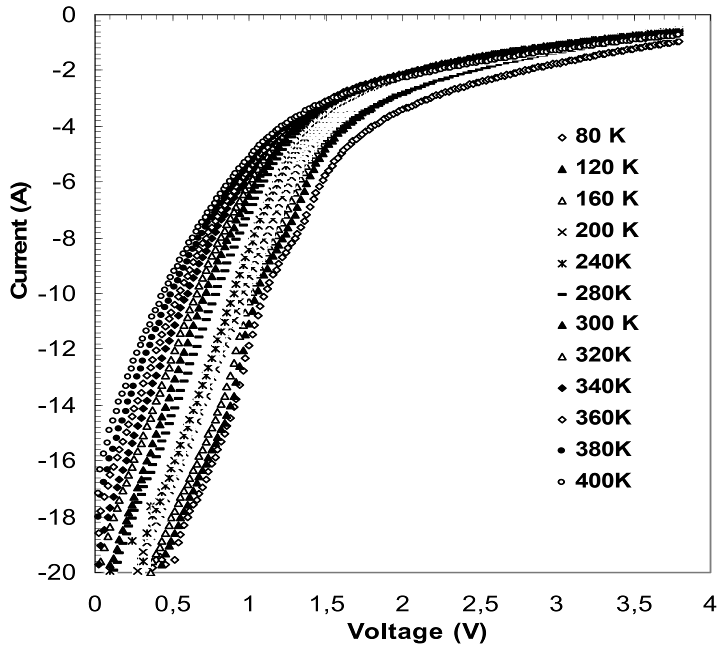

Fig.1. Forward bias semi-logarithmic LnI-V-T characteristics of Sn/p-InP SBDs.

In Fig. 2, experimental *dV/d(lnI) - I* plot is presented at different temperatures for Sn/p-InP SBDs. Eq. (3) should give straight line for the data of downward curvature region in the forward bias *I-V* characteristics. Thus, a plot of *dV/d(lnI) - I* will give R_s as the slope and *nkT/q* as the y-axis intercept. As a function of temperature, the values of *n* and R_s derived from Fig.2 and are presented in Table 1.

As can be seen in Table 1, there are an abnormal increase in the experimental values Φ_{bo} and R_s with increasing temperature while the ideality factor decrease with increasing temperature. The R_s calculated from the Cheung function shows an unusually behaviour that it increases with increase of temperature. In generally, such temperature dependence is an obvious disagreement with the reported the negative temperature coefficient of the series resistance. Such behavior was attributed to the lack of free charge at low temperature and in the temperature region where there is no carrier freezing out which is non-negligible only at low temperature [23]. At higher temperatures, the contact resistance and the resistance of outer connections are probably the prevalent sources of the R_s. Similar temperature dependence was obtained both experimentally [24] and theoretically [25].

Table 1. Temperature dependent values of various parameters determine from forward bias I-V characteristics of Sn/p-InP SBDs.

T(K)	Io(A)	n(I-V)	Φ_{Bo}(I-V)	Φ_{Beff}.(eV)	Rs(Ω)
80	6,01E-12	11,239	0,234	1,035	1,5214
120	1,35E-11	7,766	0,350	1,073	2,3871
160	2,41E-11	5,666	0,467	1,043	2,5693
200	4,09E-11	4,056	0,582	0,928	2,9136
240	8,00E-11	3,261	0,693	0,875	3,2215
280	3,60E-10	2,908	0,779	0,826	3,1332
300	7,00E-10	2,401	0,821	0,698	3,1999
320	2,60E-09	2,446	0,843	0,679	3,2156
340	4,91E-09	2,191	0,881	0,613	3,3188
360	1,60E-08	2,185	0,899	0,574	2,852
380	2,96E-08	1,992	0,933	0,520	2,4876
400	9,06E-08	2,022	0,947	0,485	2,2193

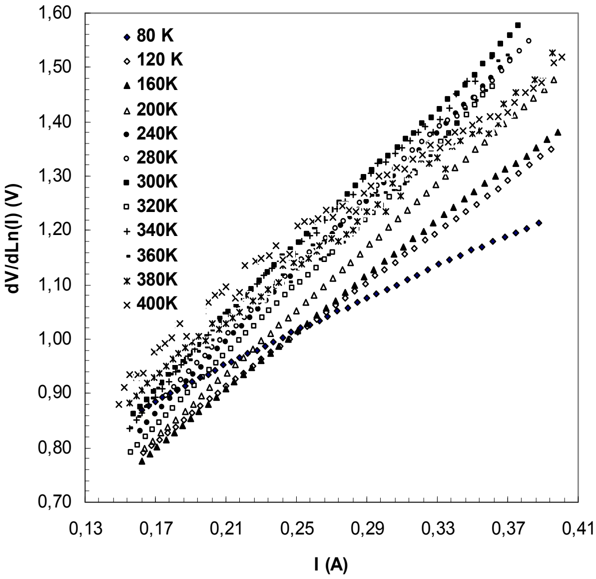

Fig.2. The characteristics dV/dLnI - I plot of the Sn/p-InP SBDs obtained from forward bias I-V data at various temperatures.

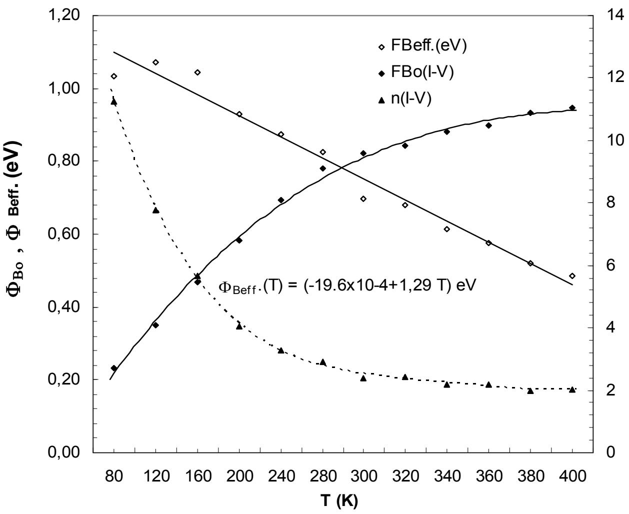

Fig.3. Temperature dependence of Φ_{Bo}, Φ_{Beff} and n for the Sn/p-InP SBDs obtained

from forward bias I-V data at various temperatures.

As can be seen from Fig. 3 and Table 1, the values of n decrease exponentially with increasing temperature. Such behavior of n is known as "*To effect*" or "*To anomaly*" [26]. Using the tunneling factor the temperature dependent barrier height Φ_{Beff} is obtained from Eq. (2) for each temperature and presented in Table 1. Φ_{Beff} is considered to be real fundamental quantity. The value of Φ_{Beff} is also shown in Fig. 3 as a function of the temperature. As can be seen from Fig. 3 and Table 1, Φ_{Beff} is always larger than zero-bias barrier below room temperature. Furthermore, the temperature dependence of the BH can be described as

$$\Phi_{Beff}\,(T) = \Phi_{Bef}\,(T{=}0\ K) + \alpha\ T \qquad (4)$$

where Φ_{Bef} (T=0 K) is the BH extrapolated to zero-temperature and α is the temperature coefficient of Φ_{Bef} (T). In Fig.3, the fitting of the Φ_{Bef} (T) yields Φ_{Bef} (T=0 K) 1.29 eV and α =19.6x10^{-4} eV/K. This value of temperature coefficient α is the agreement with the literature.

4. Conclusion

The current conduction mechanism across Sn/p-InP SBDs was carried out using *I-V* measurements in the wide temperature range of 80-400 K. The non-ideal forward bias *I-V* behaviour observed in the Sn/p-InP SBDs was attributed to a change in the MS BH due to series resistance and interfaces states. Therefore we have reported a modification, by the inclusion both of n and $ax^{1/2}\delta$ in the expression of I_0 to explain the experimental *I-V* characteristics of Sn/p-InP SBDs with a interfacial insulator layer. Thus, the validity of including n and $ax^{1/2}\delta$ in the expression of I_0 are demonstrated by comparing the corrected values of BH Φ_{bef}. In addition, the ideality factor and series resistance were determined from the intercept and slope of dV/dLnI vs I plots at each temperature. The fitting of the Φ_{Bef} (T) yields Φ_{Bef} (T=0 K) 1.29 eV and α =19.6x10^{-4} eV/K. This value of temperature coefficient α is the agreement with the literature.

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