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Extraction of the electrical parameters of the Au/InSb/InP Schottky diode in the temperature range (300 K- 425 K)

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Abstract *– In this work, we have presented a theoretical study of Au/InSb/InP Schottky diode based on current-voltage (I-V) measurement in the temperature range (300 K- 425 K). Electrical parameters of Au/InSb/InP such as barrier height (Φ_b), ideality factor and series resistance have been calculated by employing the conventional (I-V), Norde, Cheung and Chattopadhyay methods. Measurements show that the Schottky barrier height (SBH), ideality factor and series resistance, RS for Au/InSb/InP Schottky diode in the temperature range (300 K–425 K) are 0.602-0.69eV, 1.683-1.234 and 84.54-18.95 (Ω), respectively. These parameters were extracted using Atlas-Silvaco-Tcad logical.*

Keywords: *Cheung and Chattopadhyay methods, Schottky barrier, Schottky diode, SBH, Silvaco.*

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I.1. Introduction

Semiconductors of the (III-V) family have important applications in the field of electronics and optoelectronics. Recently, (III-V) semiconductors have received a great deal of attention for the fabrication of microwave devices as well as integrated circuits used in modern high-speed optical communication systems [1-4]. Among the most widely used III-V compounds are GaN, GaAs, GaP, and InP, because of their band gap to their wide band gaps, stability at high temperatures, electron mobility, hardness, low iconicity and high terminal conductivity [4-8]. InP binary compound belongs to a family of III-V semiconductors which is widely used in the manufacture of electronic components such as Schottky diode (MS), metal-isolate-semiconductor (MIS) structure, MOS, transistor,….etc [9-12]. InP binary compound is a direct band gap semiconductor with E_g = 1.423 eV and lattice parameter a= 5.869 Å at 300 K [6]. This binary is a promising material for detectors in the long-wavelength spectral region, light emitters, solar cell application, and microwave field-effect transistors [2, 13-16]. On the other hand, The InP binary compound has received a great deal of attention for the fabrication of Schottky diodes (Metal- InP). A study have investigated the forward bias current-voltage (I - V) characteristics of Au/n-InP Schottky barrier diodes (SBDs) in the temperature range of 160-400 K but by using Atlas device simulator of the software Silvaco-Tcad, have simulated the (I–V) and (C–V) characteristics of the Au/n-InP Schottky as a function of the temperature range 200–400 K [17,18]. More recently work have analyzed the microstructural, chemical and elemental composition properties of CuO/n-InP junction using X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS) and energy-dispersive X-ray spectroscopy (EDAX) techniques [19]. Another experience have prepared Graphite/InP Schottky diode and analyzed their electrical characterization, using (I–V–T) and (C–V) methods [20,21]. This work aims to present the current-voltage (I–V) measurement for Au/InSb/InP Schottky diodes in the temperature range (300 K- 425 K). The surface of the InP is restructured by an InSb's thin film of several monolayers. Electrical characteristics of Au/InSb/InP Schottky diodes, such as ideality factor (n), barrier height, and series resistance (Rs) were investigated using (I-V), Norde, Cheung and Chattopadhyay methods.

MATERIAL AND METHOD

II. 1. Current-voltage (I-V) method

The effect of the diode resistor can be modeled by a series combination of a diode and a resistor (Rs) through which the current flows. In addition, in the case, the ideal diode the value of the ideality factor (n) equals 1 while for the no ideal diode the (n) value is superior to 1 (n >1). In the case of the Schottky diode, assuming that the current is due to a thermionic emission (TE), the relation between the applied forward bias and the current can be given by [22-25].

$$\mathrm{I} = \mathrm{I_0} \exp\left(\frac{-qV}{kT}\right)\left[1 - \exp\left(\frac{q(V-IR)}{nkT}\right)\right] \quad (1)$$

Here, I_0 ,*n*, k, and T present the reverse saturation current, the ideality factor, the Boltzmann constant, the absolute temperature in Kelvin, respectively.

For the applied forward voltage (V > 3kT/q), the equation (1) can be written as [22-25]:

$$\mathrm{I} = \mathrm{I_0} \exp\left(\frac{-qV}{kT}\right) \quad .(2)$$

We could find the value of (I_0) by the plot ln (I) versus (v) at v = 0 volts. Then, by replacing the calculated (I_0) value in the equation (2), we could find the Schottky barrier height (Φ_b). The ideality factor (n) value can be extracted from the linear region of (ln (I) -v) curve (the straight line of the curve).

$$I_0 = AT^2A^* \exp\left(\frac{q\Phi_{bo}}{kT}\right) \quad (3)$$

where A is the rectifier contact area, (Φ_b) is the Schottky barrier height, The value of (Φ_b) can be deducted directly from I–V curves if the effective Richardson constant is known [22]. A^* is the Richardson constant (A^* =9.4 A/cm^2 K^2 for n-InP [26]).

The voltage (v) across the diode can then be expressed in terms of the total voltage drop v across the series combination of the diode and resistor. The value of n for an ideal diode is e is equal to one. High values of n can be attributed to the presence of the interfacial thin layer and a wide distribution of low-Schottky barrier height patches (or barrier inhomogeneities) [27].

It can also be described and expression of the voltage (v) across the diode can then out of the total voltage drop (v) across the series combination of the diode and resistor, out of which the current flows, It can be composed or formed the effect of the diode resistance can be modeled with a series combination of a diode and a resistor Rs [27].

II. 2. Cheung method

the Schottky barrier height (Φ_b), the ideality factor (n) , and the series resistance (Rs) can be calculated from a second method called Cheung and Cheung [28]. In this method, the series resistance (Rs) and the ideality factor (n) are determined by the following functions [28]:

$$\mathrm{G} = \frac{\partial \mathrm{V}}{\partial(\ln(\mathrm{I}))} = \frac{n\mathrm{kT}}{\mathrm{q}} + \mathrm{I\,Rs} \quad (4)$$

also, Schottky barrier height can be defined by Cheung's relation [28]:

(1)

$$\mathrm{H\,(I)} = \mathrm{V} - \left(\frac{nkT}{q}\right)\ln\left(\frac{\mathrm{I}}{\mathrm{AA^*T^2}}\right) = \mathrm{n}\,\Phi_{\mathrm{bn}} + \mathrm{I}R_S \quad (5)$$

II. 3. Norde method

Alternatively, another method called Norde approximation [29] can be used to calculate the two parameters that are the series resistance and the barrier height of Au/InSb/InP structure. The Norde approximation is defined as [29]:

$$\mathrm{F(v)} = \frac{\mathrm{v}}{\gamma} - \frac{\mathrm{kT}}{\mathrm{q}}\ln\left(\frac{\mathrm{I(v)}}{\mathrm{AA^*T^2}}\right) \quad 6)$$

Here, γ is an integer (dimensionless) greater than n (n=1.84), and I (V) present the current which is acquired (3) from the (I–V) curve. In this approximation, Φ_b and Rs values can be determinate by using the following relations [29, 30]:

$$\Phi_b = \mathrm{F(v_0)} + \left[\frac{\mathrm{v_0}}{\gamma} - \frac{\mathrm{kT}}{\mathrm{q}}\right] \quad (7)$$

$$\mathrm{Rs} = \frac{\gamma - n}{I} - \frac{kT}{q} \quad .(8)$$

where (n) value is obtained from the ln I-V curve, $\mathrm{F(v_0)}$ is the minimum point of $\mathrm{F(v)}$ the plot, (V) is the corresponding voltage and $(\mathrm{I_0})$ is present the current corresponding to (V_0) in the I–V characteristic.[31]

II. 4. Chattopadhyay model

In addition, Chattopadhyay model can be also used to determine the ideality factor and barrier height values of the Schottky diode. In the present model, the barrier height Φ_b can be written as [32]:

$$\Phi_b = \Psi_s(\mathrm{J_C}, \mathrm{V_C}) + \mathrm{C_2V_C} + \mathrm{V_n} - \frac{\mathrm{kT}}{\mathrm{q}} \quad (9)$$

Where, $\Psi_s(J_C,V_C)$ present the critical surface potential, V_C is the critical voltage, V_n is the potential difference between the Fermi level and bottom of the conduction band, and (C_2) present the parameter inverse of the diode ideality factor[31].
The critical surface potential value ($\Psi_s(J_C,V_C)$) can be determined by the following relation [32, 33]:

$$\Psi_s = \frac{kT}{q}\ln\left(\frac{AA^*}{I}\right) - v_n \tag{10}$$

And V_n Parameter can be calculated from the following relation:

$$v_n = \frac{kT}{q}\ln\left(\frac{N_c}{N_d}\right) \tag{11}$$

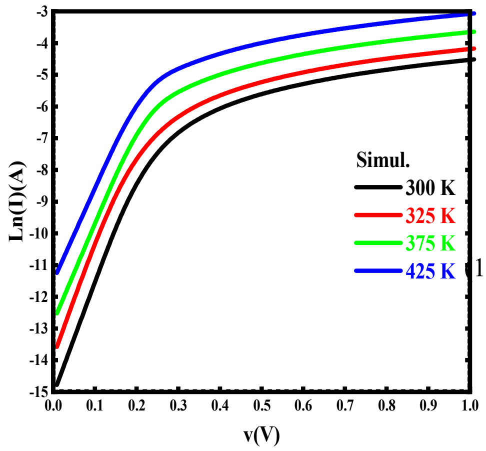
Here, N_C and N_d are the effective conduction band density of states and the carrier concentration, respectively. Using relation (9), we have calculated V_n for different temperatures (300K, 325K, 375K, and 425K). Theirs obtained values are 0.04eV, 0.044 eV, 0.0512 eV, and 0.581eV, respectively.
In order to determinate the inverse of the ideality factor (C_2), we have used the following relation [32]:

$$C_2 = \frac{1}{n} = \left(\frac{d\Psi_s}{dV}\right)_{Jc,V_c} \tag{12}$$

III. Result and discussions

III.1. Results of current-voltage (I-V method)

Figure 1 shows our simulated current-voltage (I-V) characteristics of Au/InSb/InP Schottky diode, using Atlas-Silvaco-Tcad soft word, at some selected temperature (300,325,375and 425 K). From Figure 1, (I–V) characteristics plot show that the Au/InSb/InP structure has a Schottky diode behavior. In addition, we remarked that all curves have similar behaviors with a qualitative difference. In addition, we observed that there is a deviation of the current and voltage characteristics of the linear. This deviation can be due to the series resistance (Rs). Our obtained results of saturation current (I_0), barrier height (Φ_b) and ideality factor (n) are shown in Table 1.



(10)

Figure .1. The (I–V) characteristics of Au/InSb/InP Schottky diode in the temperature range (300–425 K).
(11)

III.2. Results of Cheung method

Figure 2 shows the obtained of $\left(\frac{dV}{d(\ln(I))}\right)$ and H(I) as a function of (I) for Au/InSb/InP structure, at different temperatures(300, 325, 375, and 425K).

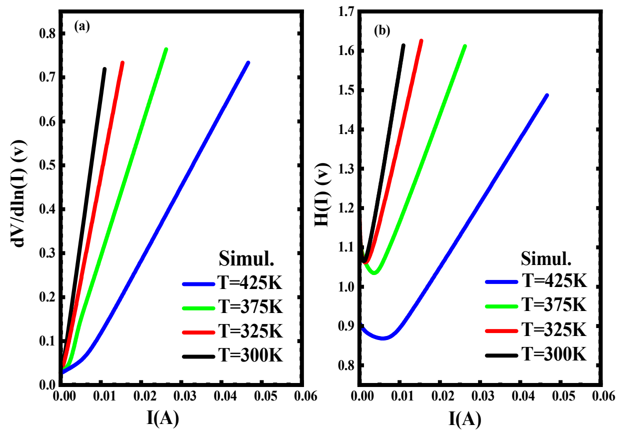


Figure.2. the obtained of $\left(\frac{dV}{d(\ln(I))}\right)$ and H (I) as a function of (I) for Au/InSb/InP Schottky diode, at different temperatures

The curve $\left(\frac{dV}{d(\ln(I))}\right)$ is fitted to a straight line and using (4). Both parameters ideality factor (n) and series resistance (Rs) have been extracted from the intercept and the slope of the line. We defined the function H (I) by replacing the value of (n) and the characteristics (I-V) in equation (5). The plot of H (I) as a function of (I) at different temperatures is shown in Figure 2 b. According to the Cheung method, the two parameters the height of the Schottky barrier (Φ_b), and the series resistance (Rs) can be determined [31, 34]. Where (Φ_b)

value is given by (y-axis) intercept of H (I) and (Rs) value is given by the slope. The obtained results of (n, Rs and(Φ_b) are shown in Table 1.

III.3. Results of Norde method

Figure 3 shows the variation of Norde's function $(F(v)$ as a function of V obtained from forward bias current-voltage characteristics of the Au/InSb/InP structure.

Our obtained results of barrier height (Φ_b) , series resistance (R_S), $F(v_0)$ and (V_0) are shown in Table 1. From Figure 3 (a), our determinate values of $F(v_0)$ and (V_0) are 0.529 V and 0.24 V, respectively, at T=300K.

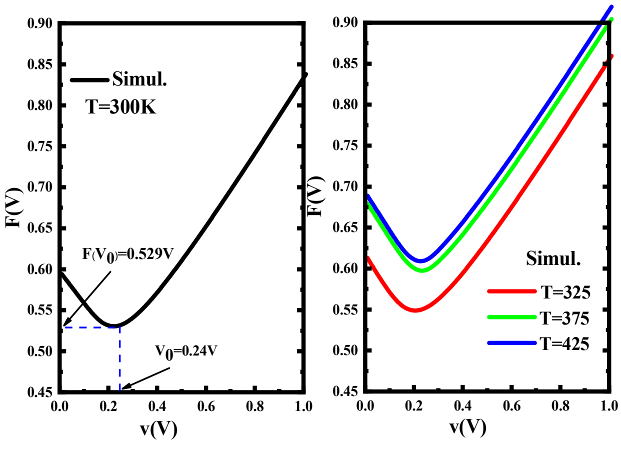


Figure.3. F (V) as a function of V obtained from forward bias current-voltage characteristics of the Au/InSb/InP Schottky diode (a) at T=300K and (b) for T=(325, 375 and 425K)

III.4. Results of Chattopadhyay model

Figure 4 shows the surface potential-forward voltage curves $(\Psi_s - V)$ of Au/InSb/InP structure for different temperatures (**300**K, 325K, 375K, and 425K).

From $(\Psi_s - V)$ behavior shown in Fig.4, we remarked that the Ψs decreases with the increases of V and Ψs value increases with the temperature (T). As showed in Fig. 4a, the critical values of (V_c) and Ψs were extracted from the curve of Ψs and the slope indicated in (red dashed line). The obtained results of the critical values (V_c) and $\Psi_s(J_C, V_C)$, and barrier height (Φ_b) using, Chattopadhyay model, are shown in Table 1.

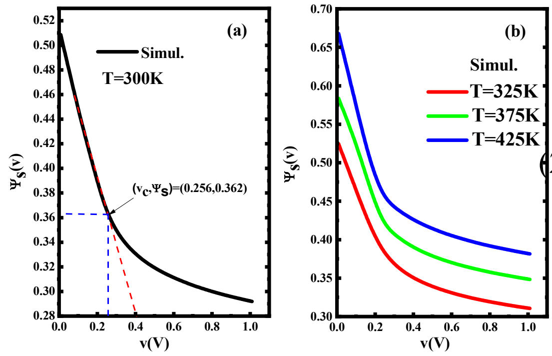


Figure. 4. Surface potential-forward voltage curves of the Au/InSb/InP Schottky diode

According to what we found, we observed that the increases in temperature are accompanied by the decreases in the ideality factor and increases in the barrier height for all methods. These phenomena are due to the no pure thermionic emission current (TE) in the device [35, 36]. Because the charge carriers have no enough energy to cross the high barrier height into those low temperatures, but current transport is provided by lower parts of barrier height [37]. and also, we have remarked that the (Rs) value decreases with increasing temperatures. This decreases can be due to the increase of the free carrier concentration at low temperatures [38] . Also, the obtained results of (R_S), using the four different methods, are slightly different.

This different in the values of R_S, is due to the different regions of (I-V) characteristics where we have determinate this quantity. In the case of the (I-V) method, we have employed the non-linear region while for Cheung and Norde methods we have used the linear region [19, 27].

The differences in the barrier height values, obtained from these methods, maybe due to the extraction of data from different regions of the forward-bias (I-V) plot [19, 33,39], where the Cheung's functions are only accomplished for the non-linear region of forward bias (I–V) curve and the Norde's function are executed for the whole forward bias region of the current-voltage curve of the diode [40]. Our obtained value of barrier height and ideality factor, for both methods (Ψs –V) and (I-V) [33]. The obtained results of(Φ_{b0}), (n) and (R_S) parameters for Au/InSb/InP Schottky diode via (I-V) method, Norde method, Cheung method, and Chattopadhyay model are summarized in Table 1.

Table .1. The obtained values of saturation current, barrier height, ideality factor, series resistance, surface potential (Ψ_s), and critical voltage for Au/InSb/InP Schottky diode in the temperature range (300 K–420 K)

Temperature	300 K	325 K	375 K	425 K
From (I- V) characteristics				
Saturation current 10^{-5}(A)	2.6	0.112	0.365	1.01
Barrier height, (Φ_b) (eV)	0.602	0.611	0.674	0.690
Ideality factor, *n*	1.683	1.624	1.362	1.234
Series resistance, R_S (Ω)	84.54	60.86	37.12	18.95
From Cheung' s method (d V/dln I) versus I				
Series resistance, R_S (Ω)	68.25	45.18	38.31	19.32
Ideality factor, n	2.011	1.927	1.674	1.312
From Cheung' s method H(I) versus I				
Series resistance, R_S(Ω)	62.01	45.18	27.72	16.55
Barrier height (Φ_b) (eV)	0.492	0.510	0.566	0.594
From Norde's method				
Barrier height (Φ_b)(eV)	0.626	0.623	0.681	0.692
Series resistance, R_S (Ω)	646.1	633.8	315.2	206.1
F (V_0) (V)	0.526	0.548	0.592	0.605
V_0 (V)	0.240	0.210	0.230	0.220
From Chattopadhyay 's method				
Barrier height, (Φ_b)(eV)	0.526	0.541	0.605	0.644
Ideality factor, *n*	1.660	1.542	1.422	1.247
surface potential Ψ_s (V)	0.362	0.391	0.424	0.463
the critical voltage (V)	0.256	0.211	0.237	0.226

IV. Conclusion

In this paper, Au/InSb/InP Schottky diodes were prepared and their electrical were studied by employing (I–V) measurements in the temperature range of (300K – 425 K). The main parameters such as ideality factor (*n*), barrier height (Φ_b), and series resistance (Rs) values were determined using four different methods (conventional (I-V), Norde, Cheung, and Chattopadhyay methods). The obtained values of these parameters are in excellent agreement with each other.

For all methods, it is observed that the increase in temperature increases the zero-bias barrier heights and decreases the ideality factor and series resistance. The nature and origin of the decrease in the ideality factor and the increase of the height barrier with the temperature for Au/InSb/InP Schottky diode have been explained based on the thermionic emission with Gaussian distribution of barrier heights.

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