Effects of Thermal Annealing on Temperature-Dependent Current-Voltage Characteristics (*I*-*V*-*T*) of the Au/*n*-InP/In Schottky Diodes

F. E. Cimilli Çatır*

**Erzincan University*, Vocational School, *Department of Electronic Technologies*, Erzincan, *Turkey*

Abstract — *The Au/n-InP/In Schottky diodes fabricated using n-type InP (100) wafer and the current voltage (I-V) characteristics were calculated according to the sample temperature between 300-70 K with 10K steps after annealing the sample at 400^{o}C in N_2 atmosphere for 3 min. The values of the barrier height obtained from I-V measurements for annealed Au/n-InP/In Schottky diodes vary from 0.570, (300 K) to 0.034, (10 K) while the ideality factors vary from 1.008 (300 K) to 3.150 (10 K). The mean barrier height was found to be 0.75 eV and the Richardson constant (A*) values as 0.921 eV and 18.48 Acm^{-2}K^{-2}, respectively. It is observed that the barrier heigth values determined from I-V measurements increased after annealing at 400^{o}C while the ideality factor values decreased. Temperature dependent barrier height values of annealed (at 400^{o}C) Au/n-InP/In Schottky contacts is consistent with "the barrier inhomogeneous model" of Schottky diodes. Because of accompanying two different mean barrier height values to the schottky diodes for the 70-150 K and 150-300 K temperature ranges, barrier height matches with the double Gaussian model of barrier height.*

Keywords — *Schottky barrier diode, barrier inhomogeneity, n-type InP, I-V-T characteristics*

I. INTRODUCTON:

Metal-semiconductor contacts play an important role in integrated circuit technology [1-3]. Fabrication of III-IV compound semiconductors with wide band gap has been important in various electronic and optoelectronic circuits in recent years [4-8]. Lately, III-VI compound semiconductors, especially InP semiconductor is of great importance as a material because of their advantages in the use of the solar cells, laser diodes, photo detectors and high speed metal-semiconductor field effect transistors (MISFETS), microwave sources, high power and high frequency low noise amplifiers [9, 10]. In addition to elemental silicon in metal-semiconductor contact fabrication, InP has begun to be considered as an alternative to GaAs, which is used for high speed and high power circuit element applications. Thus, the Schottky barrier height of InP metal contacts has been investigated by many researchers [11]. As an example, for Au/n-InP Schottky diodes, Newman et al. [12] have obtained a value of 0.51 eV at room temperature. Çetin and Ayyıldız [6] studied the temperature dependent electrical chatacteristics of the Au/n–InP and has found to be 0.42 eV for barrier height. Çakıcı et al. [13] found barrier heights values of 0,63 eV for as-deposited Au/n–InP/In diodes, 0.70 eV for annealed 100^{o}C and 0.88 eV for annealed 200^{o}C, respectively. We have already been evaluated Φ_{eff} and n values from the temperature-dependent forward-bias *I-V* characteristics between 70 to 240 K and they evaluated the experimental values of Φ_{eff} and n for the device range from 0.57 eV and 1.07 (at 300K) to 0.20 eV and 3.03 (at 70K), respectively [14]. They have indicated that the the temperature-dependent Au/n-InP Schottky contact strongly affected by the barrier inhomogeneity. The distribution of local effective Schottky barrier heights (SBHs) has been modeled by the double Gaussian barrier heights which represents the high- and low-barrier of the full distribution in 170–300 and 70–170 K temperature ranges. Shankar Naik et al. [15] studied the *I-V-T* and *C-V-T* characteristics of double metal/n-InP Schottky diodes and have estimated the SBH of Ni/Au Schottky contact is in the region of 0.38 eV (*I*–*V*), 0.93 eV (*C*–*V*) at 210 K and 0.70 eV (*I*–*V*), 0.73 eV (*C*–*V*) at 420 K, respectively. They have been observed that the ideality factor decreases while the BH increases with increasing temperature and this behavior has been interpreted by the assumption of a Gaussian distribution of BHs due to the barrier inhomogeneities of Schottky diodes.

On the other hand, it is difficult to obtain a metal/n-InP Schottky diode with a high barrier from 0.5 eV, due to its high reverse leakage current [16]. Thus, the use of n-InP for this purpose is restricted. It is known that barrier height is an important parameter for Schottky diodes because it emphasizes the band bending of the depletion layer and controls the electron transport mechanism of the Schottky diode at the metal-semiconductor interface [17]. Thermal annealing is one of the methods using to enhance the electrical performance of the Schottky diodes and many studies have been in progress to investigate the effect of thermal annealing on diode parameters [13, 18-20].

In this study, current-voltage (*I-V*) characteristics of Au/InP contacts thermally annealed at 400^{o}C are obtained. Various diode parameters have been calculated from these characteristics. In addition, annealing at 400^{o}C is performed to examine the effect of annealing on these parameters. By taking *I-V* measurements at different temperatures, the dependence of the diode parameters on the temperature is investigated, the effect of thermal annealing on electrical parameters of the Au/InP Schottky contacts is experimentally measured and compared to the values of as-deposited Au/n–InP/In diodes reported in our previous study [14].

II. EXPERIMENTAL

The Schottky barrier diodes (SBDs) were prepared using *n*-type InP (100) wafer. The wafer was degreased consecutively in trichloroethylene, acetone, and methanol for 5 min. The degreased wafer was etched with H_2SO_4:H_2O_2:H_2O (5:1:1) for 1 min to remove the surface damages and undesirable impurities. The backside ohmic contact was made by evaporating In and annealing at 300^{o}C in an N_2 atmosphere for 3 min. The Schottky contacts were formed on the front face of the pieces as dots with a diameter of about 1.0 mm by evaporation of Au, (diode area =7.85x10^{-3} cm^2). All evaporation processes were carried out in a vacuum coating unit at about 10-6 mbar. To analyze the effect of annealing, the Au/n-type InP Schottky diodes have been annealed at 400^{o}C for three minutes in flowing N_2. The *I-V* characteristics of the devices were measured in the temperature range of 20-300 K using a temperature controlled ARS Closed Cycle 4K He cryostat. Keithley 6514 electrometer and 2400 sourcemeter used for *I-V* measurements. Depending on annealing temperature, the change of the electrical characterization of the device has been examined.

III: RESULTS AND DISCUSSION

Current transport in an ideal Schottky contact is due to majority carriers and it may be described by Thermionic Emission theory (TE) over the interface barrier. TE current at the forward bias can be written as [4]

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

where the saturation current I_0 and the saturation current density I_0 are defined by

$$I_0 = AA^*T^2 exp\left(-\frac{e\Phi_b}{kT}\right) \qquad (2)$$

The expressions A, A^*, T, q, k and Φ_{b0} are the diode area, the effective Richardson constant, temperature in Kelvin, the electronic charge, Boltzmann's constant and the zero-bias barrier height (apparent barrier height), respectively. The ideality factor n describe the information about the ideality of the device and deviation of the experimental *I-V* data from the ideal TE model using the definition

$$n = \frac{e}{kT}\frac{dV}{d(\ln I)} \qquad (3)$$

and the barrier height (BH) From Eq. (1), can be written as

$$e\Phi_b = kTln(A\,A^*T^2 / I_0) \qquad (4)$$

Semi-logarithmic forward-bias *I-V* characteristics of the Au/n-InP Schottky diode annealed at 400^{o}C presented in Figure 1 shows increasingly linear behaviour over several orders of current with decrease in temperature in the 70-300 K range. The barrier hight values of the annealed (at 400^{o}C) Au/n-InP/In Schottky diodes vary from 0.570 (300 K) to 0.034 (10 K) while the ideality factors vary from 1.008, (300 K) to 3.150 (10 K). As seen in these plots, the ideality factor increases with decreasing temperature, whereas the zero-bias barrier height decreases with decreasing temperature and could be expressed by the barrier inhomogeneity of thermionic emission mechanism. As we compare the barrier height values obtained from *I-V* measurements to as-deposited Au/n-InP/In Schottky diodes [14] we can see the barrier heights increased by annealing proces while the ideality factors decrease.

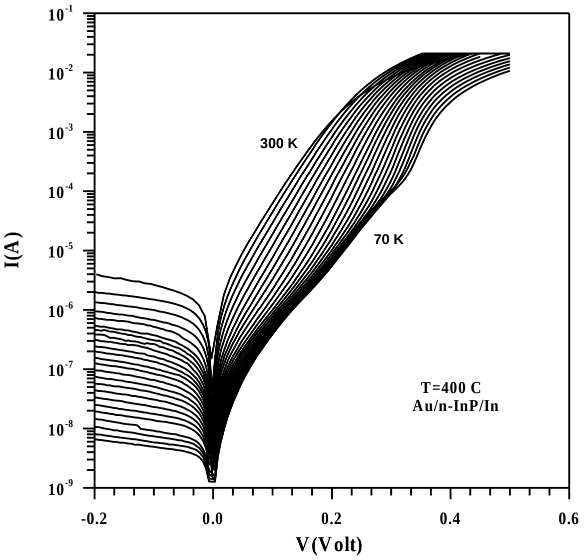

Fig. 1. The *I-V* characteristics of Au/n-InP/In Schottky diodes annealed at 400^{o}C.

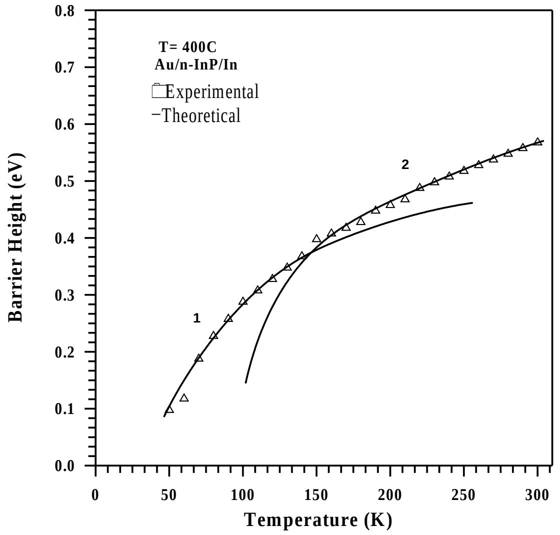

Fig. 2. The barrier heights versus temperature plot of of Au/n-InP/In Schottky diodes annealed at 400°C.

The temperature dependent barrier heights and the ideality factors are given in Figure 2 and 3. for Au/n-InP/In Schottky diodes annealed at 400°C with theoric fit values. These plots are consistent with "the barrier inhomogeneous model" of Schottky diodes. Because of accompanying two different mean barrier height values to the Schottky diodes for the 70-150 K and 150-300 K temperature ranges, barrier height matches with the double Gaussian model of barrier height.

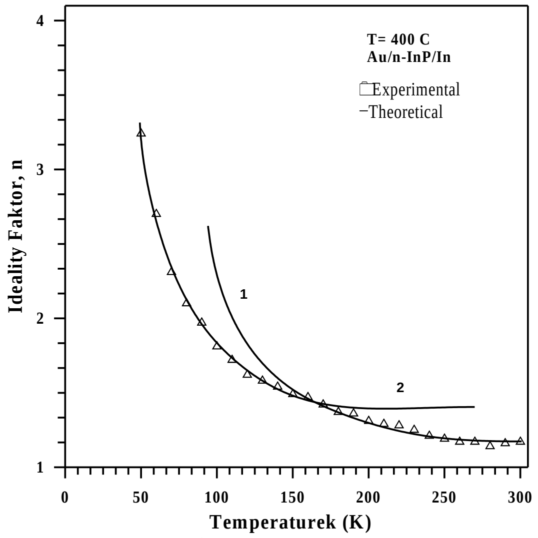

Fig. 3. The ideality factors versus temperature plot of of Au/n-InP/In Schottky diodes annealed at 400°C.

The lateral inhomogeneity of the barrier affected the temperature dependent *I–V* characteristics and the value of the Richardson constant obtained from *I–V* characteristics as a function [21, 22]. For the consideration of the effective BH, the Richardson plot of saturation current. Eq. (2) can be written as

$$\ln\left(\frac{I_0}{T^2}\right)=\ln\left(AA^*\right)-\frac{e\Phi_b}{kT} \qquad (4)$$

The conventional Richardson plot is usually defined as $\ln(I_0/T^2)$ versus 1/kT plot given in Figs. 4 and 5. The linear portion of the experimental plot in Fig. 4 is seen to fit asymptotically with a straight line yielding a mean barrier height value value of 0.75eV for Au/n-InP/In Schottky diodes annealed at 400°C. Moreover, the modified Richardson plots, $ln(I_0/T^2)-q^2\sigma^2/(2k^2T^2)$ versus$1/kT$ for is also reported in Figure 5. The BH values of 0.58 and 0.25 eV and the Richardson constant values for the Au/n-InP/In Schottky diodes annealed at 400°C are found to be A^*_1=9.21 and A^*_2=18.48 A/K^{-2}cm^{-2}, respectively. These values agree with the real value of Richardson constant, 9.4 A/K^{-2}cm^{-2}given in the literature. After annealing procedure the the mean value of barrier height shows a significant increase from 0.53 eV [14] to 0.75 eV.

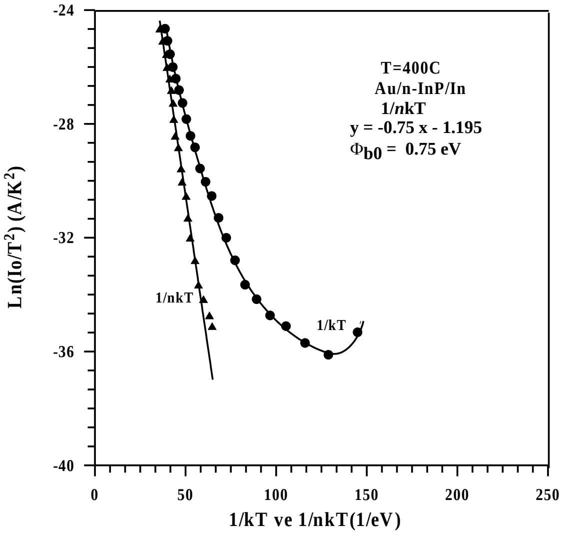

Fig. 4. The Richardson plots of of Au/n-InP/In Schottky diodes annealed at 400°C.

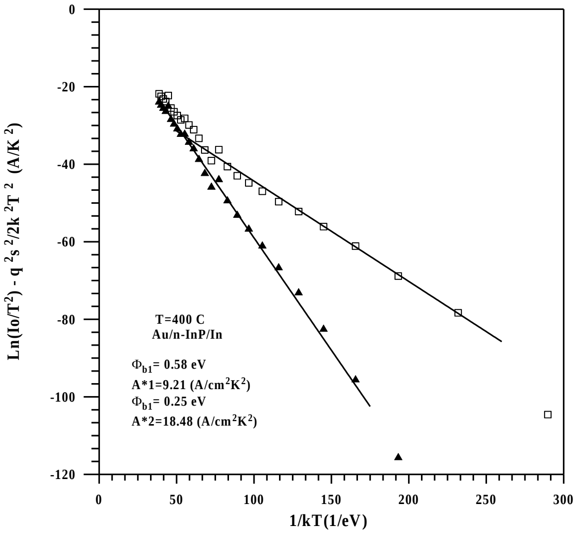

Fig. 5. The modified Richardson plots of of diodes annealed at 400°C.

As indicated above the conventional Richardson plots has shown non-linearity at low temperatures these discrepancies can be explained by the Gaussian distribution of the barrier height. In Figure 5, two values of Φ_b and Richardson constant supports the idea of the barrier inhomogeneous model of Schottky diodes with the double Gaussian model of barrier height.

III. CONCLUSION

The effect of thermal annealing on experimental *I-V-T* characteristics of the Au/n-InP/In Schottky diodes (annealed 400^{o}C) is discussed with using the traditional thermionic emission (TE) model. The certain diode parameters of ideality factor and the barrier height values were obtained from electrical measurements of the annealed Au/n-InP/In Schottky barrier diodes. The value of mean barrier height of the contact was found to be 0.75 eV. Furthermore, it is shown that the SBH values increases and the ideality factors decreasing with annealing at 400^{o}C. The temperature dependent *I-V* characteristics were modeled by the double Gaussian distribution (GD). The deviations from linearity, the presence of double GD and the variation of the Richardson plots were attributed to the effect of the Schottky barrier inhomogeneities. As the ideality factor is an exhibition of the uniformity, it is foreseen that the diode parameters should be enhanced by improving the uniformity of metal semiconductor interlayer by annealing 400^{o}C temperature.

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