Electrical and Structural Transport characteristics of Ni/Ti Schottky contacts to n-type Indium Phosphide (InP)

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Abstract — *This article mainly studies about the current transport mechanism of Ni/Ti bilayer contact on n-InP Schottky barrier Diode. At −1 V, the reverse leakage current of the as-deposited Ni/Ti Schottky contact is* 8.829×10^{-10}*A. For contacts annealed at 200 ℃, 300 ℃ and 400 ℃, the reverse leakage current increases. The corresponding values are* 1.111×10^{-9}, 1.329×10^{-9} *and* 1.649×10^{-9}*A at -1 V. The investigated value of SBH of the as-deposited Ni/Ti Schottky contact is 0.81 eV. On observation, it is found that there is decrease of SBH for contacts annealed at 200 ℃ and 400 ℃. At the same time, the relevant values are 0.80 eV, 0.79 eV and 0.78 eV, respectively. The calculations show that 0.85 eV is the SBH of as-deposited ni/Ti//n-InP Schottky diodes. The same are 0.83 eV at 200 ℃ and 0.79 eV at 400 ℃ annealed contacts respectively. It is observed that the as-deposited Ni/Ti/n-InP contact has the highest SBH as compared to SBH of annealed contacts. Also, these values are in good agreement with the values arrived from the I-V method. The annealing effects on electrical and structural properties are employed for this study.*

Keywords—*Schottky barrier Diodes; Ni/Ti/n-InP; I-V Studies; XRD analysis.*

I. INTRODUCTION

Because of their important and vital physical and chemical properties, III-V compound semiconductors, indium phosphide (InP), notably, have turned out to be an area of considerable research [1]. InP is an extremely suited substrate for a large number of applications such as high-temperature, high-frequency and high-power devices due to a direct transition optimum band gap and high-electron mobility [1, 2, 3]. It is notable that as result of investigations on Schottky contacts, barrier heights in the range of 0.40 - 0.55 eV have been found. This may be the chemical reaction and/or out-diffusion occurring on the metal–InP interface producing interfacial layers. Contribution to the barrier is by local charge redistribution and/or change of effective work function at the interface [4]. The development of high quality metal-semiconductor (MS) structure, consequently, turns out to be important. This is because the electrical characteristics of the Schottky barrier diode (SBD) depends heavily on the quality of MS interface. However, high barrier height and low-reverse leakage current SBDs even today remains a challenge. The part of our work is secondly focus as to study Ni/Ti bi-layers at various annealing temperatures on InP. A large barrier height will be induced by a good Schottky contact, resulting in better device characteristics. A large number of bilayer schemes are made on n-InP as a Schottky contact; a better and highly reliable one has not yet been formed. The strength of interfacial reactions determines the quality of Schottky barriers in InP, many times between the metal and semiconductor. Titanium (Ti) has been selected as the first Schottky layer in this work, because of its low work function and its capacity to provide for the lowest voltage drop. Nickel (Ni) is preferred over titanium as a second layer because it's high degree of chemical inertness and thermal stability. Unfortunately, even today, very little information is available regarding the effect of annealing, more notably, regarding rapidly thermal annealing (RTA) on structural and electrical properties of metal/InP Schottky contacts. So, the structural, electrical and surface morphological properties of the Ni/Ti bilayer on n-InP at different annealing temperatures are investigated in the present work.

II. EXPERIMENTAL PROCEDURES

(Undoped n-InP (100) wafer which was polished one side was used in this work, which was grown by the Liquid Encapsulated Czochralski (LEC). This had a carrier concentration of about 4.5×10^{15} cm^{-3}. Organic solvents like trichloroethylene, acetone and methanol were used to cleanse the wafer in order to remove undesirable impurities and surface damage layer. Ultrasonic agitation was used in sequence of five minutes each and rinsed in de-ionised (DI) water for 30 s and high-purity nitrogen was used for drying. Also, HF (49%) and H_2O (1:10) were used for 60 s to etch the samples; this was done for removal of native oxides from the wafer surface. Thermal evaporating of indium (50 nm) was done on the rough side of the InP wafers to form an ohmic contact followed by thermal annealing. Ti (20 nm)/Ni (30 nm) metals are evaporated as dots on the n-InP surface. Also, the diameter of ohmic contact film was kept 0.70 mm through a stainless-steel mask. For this purpose, e-beam evaporation system was used. A vacuum pressure of 5.0 X 10^{-6} mbar was applied to carry out all evaporations processes. Sequential annealing was done on the Schottky contacts at 200 °C and 400 °C in a RTA system for 60 s in N_2 ambient for investigating thermal annealing effects.

Keithley source measure unit (Model No. 2400) as well as automated deep level spectrometer (SEMILAB DLS-83D) has employed to investigate the I-V characteristics. The interfacial reactions were characterized by X-ray diffraction (Bruker AXS: D8 diffractometer).

III. RESULTS AND DISCUSSION

A. *Current-Voltage (V-I) Characteristics*

Fig.1 shows the current-voltage (I-V) characteristics of the Ni/Ti/n-InP Schottky diodes before and after annealing at 400 °C. At −1 V, the reverse leakage current of the as-deposited Ni/Ti Schottky contact is 8.829×10^{-10}A.

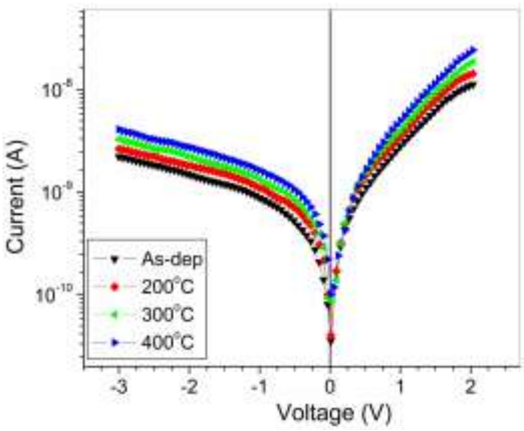

Fig 1: Forward and reverse bias I-V characteristics of Ni/Ti/n-InP SBD

For contacts annealed at 200 °C, 300 °C and 400 °C, the reverse leakage current increases. The corresponding values are 1.111 X 10^{-9}, 1.329 X 10^{-9} and 1.649 X 10^{-9}A at -1 V. At increased annealing temperatures, the leakage current increases significantly in comparison with as-deposited one. In order to determine the SBH and n, the forward bias characteristics in terms of thermionic emission (TE) theory (at V≥3kT/q) over the barrier can be employed as [1]

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

where

$$I_o = AA^{**}T^2 \exp(-q\phi_b/kT) \quad 2$$

Here I_0 = reverse saturation current
V = applied voltage
k = Boltzmann's constant
n = ideality factor
A = effective diode area
A^{**} = effective Richardson constant (for n-InP A^{**} is 9.40 $Acm^{-2}K^{-2}$)
q = charge of the electron and
T = absolute temperature.

The SBH can be calculated from the equation

$$\phi_b = kT/q \ln(AA^{**}T^2/I_o) \quad 3$$

The investigated value of SBH of the as-deposited Ni/Ti Schottky contact is 0.81 eV. On observation, it is found that there is decrease of SBH for contacts annealed at 200 °C and 400 °C. At the same time, the relevant values are 0.80 eV, 0.79 eV and 0.78 eV, respectively. It is disclosed by experiments that better rectification is exhibited by the as-deposited contact in comparison with annealed contacts. There is a possibility that metals may react with semiconductors resulting in the formation of new compounds during the annealing process. So, the change in SBH may be because of the combined effects of phase transformation and interfacial reaction [5]. The effect of temperature on defect sites in the phosphide semiconductor may lead to decrease in SBH upon annealing at 400 °C. It shows that the annealing temperature strongly influences electrical properties of the Ni/Ti/n-InP. It is the opinion of Duboz et al. [6] that a reduction in the density of interfacial defects can lead to the lower value of the barrier height for the respective sample. It is possible to estimate the ideality factor (n) from the slope of the linear region concerning the forward bias ln (I) versus V plot. The ideality factor n is defined as

$$n = \left(\frac{q}{kT}\right)\left(\frac{dV}{d(\ln I)}\right) \quad 4$$

By this calculation, 1.16 is the ideality factor of Ni/Ti Schottky contact for the as-deposited contact. The ideality factor n values are 1.23, 1.45 and 1.60 for 200 °C, 300 °C and 400 °C temperatures respectively. The ideality factors of Ni/Ti Schottky contacts are higher than the unity. This is because of the states associated with the defects at the surface. The interface states, inter-diffusion, compound formation, etc can derive from thermodynamically thermal annealing [7]. This leads to recombination centers [8] and SBH inhomogeneities [9]. A flow of excess current may be caused by this. This may also lead to a deviation from the ideal TE behavior. Defect states in the band gap of the semiconductor, providing other current transport mechanism may result in a high ideality factor. It may be barrier tunneling or generation recombination in the space charge region [10]. It has been found that the amount of transferred charge increases, as the annealing temperature increases. This creates more defects in the InP which is close to the interface as well as inside the interfacial layer. The increase in value of the ideality factor may be because of these defects. Interface dipoles may be the other possibility for higher values of ideality factor. This may be caused by an interface and also fabricated induced defects at the interface [11]. Also, the high ideality factor increases the leakage current caused by generation-recombination process, as a result, the rectification ratio of the diode decreases.

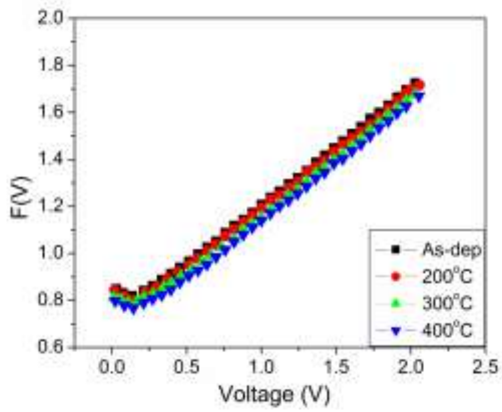

Fig 2: Plot of F(V) against Voltage V for Ni/Ti/n-InP SBD

Moreover, the Schottky barrier height (ϕ_b) of the SBDs are determined using the Norde method [12]. This method involves a Norde function, F(V), being plotted against V, which is shown in Fig. 2 and the F(V) is given by

$$F(V)=(V/\gamma) - KT/q \ln[I(V)/AA^{**}T^2] \quad 5$$

where γ is a dimensionless integer, I(V) is the current, which is determined from I-V characteristics. The effective SBH (ϕ_b) is calculated by

$$\phi_b=F(V_o) + (V_o/\gamma) - KT/q \quad 6$$

where $F(V_0)$ is the minimum value of F(V), and V_0 is the corresponding voltage. The calculations show that 0.85 eV is the SBH of as-deposited Ni/Ti//n-InP Schottky diodes. The same are 0.83 eV at 200 °C, 0.81 eV at 300 °C and 0.79 eV at 400 °C annealed contacts respectively. It is observed that the as-deposited Ni/Ti/n-InP contact has the highest SBH as compared to SBH of annealed contacts. Also, these values are in good agreement with the values arrived from the I-V method. It has been clearly noted that with the increase in the RTA temperature, the SBH of the Ni/Ti Schottky contacts decrease.

IV. TABLE I

DIFFERENT PARAMETERS OF NI/TI/N-INP SBD AS A FUNCTION OF ANNEALING TEMPERATURE

Parameter	**As-dep**	**200 °C**	**300 °C**	**400 °C**
Reverse Leakage current (A)	8.829 $\times 10^{-10}$	1.111 $\times 10^{-9}$	1.329 $\times 10^{-9}$	1.649 $\times 10^{-9}$
Schottky barrier height (ϕ_b *in* eV)	0.81	0.80	0.79	0.78
Ideality factor (*n*)	1.16	1.23	1.45	1.60

B. Structural Characteristics

1) XRD analysis:

The annealing temperature dependent of the present investigated Ru/Ti/n-InP Schottky diode was performed by X-ray diffraction (XRD) measurement. Fig. 3 shows the XRD plots of the Ru/Ti/n-InP Schottky diode at different temperatures. Fig. 3(a) shows the XRD plot of the as-deposited sample. In addition to the characteristic peaks of InP (2 0 0), (4 0 0), other peaks are also observed. These peaks are identified as In_3Ni (2 2 2), NiP_4 (1 2 3). Fig. 5.10 (b) shows the XRD plot of the contact annealed at 200 °C. We find from the plot that a new interfacial phase was formed while we observe an additional peak beside as-deposited case. Also, this peak is identified as Ti_3P (1 0 2).

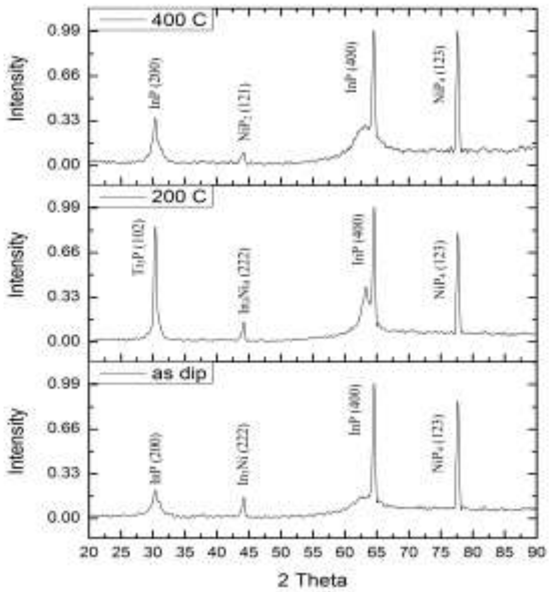

Fig 3: Different XRD plots of Schottky diode Ni/Ti/n-InP.

In the XRD plot of the contact annealed at 400 °C (Fig. 3 (c)), there is an extra peak, which is identified as NiP_2 (1 2 1).

V. CONCLUSIONS

I-V and XRD measurements at different annealing temperatures were employed to analyze the electrical, structural properties. The electrical parameters of the fabricated Ni/Cu Schottky diode exhibit good electrical properties after rapid thermal annealing up to the temperature, 400 °C. The values of Schottky barrier height (SBH) and ideality factor n at room temperature (as-deposited) were 0.81 eV (I-V) and 1.16 respectively. The SBH slightly decreased from 0.80 eV to 0.78 eV in the I-V plots when the annealed temperature increased from 200 °C to 400 °C. However, the ideality factors increased from 1.23 to 1.60 with the same temperature variation. The observations revealed that the SBH decreased and ideality factor increased with the annealing temperature. XRD results showed that the formation of phosphide phases at the Ni/Ti/n-InP interface. Because of this reason SBH is decreased upon annealing temperatures.

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