

# Interface states and electrical properties of Cu/Ni Schottky contacts on n-InP substrate

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**Abstract:** The Cu/Ni Schottky contact on n-InP substrate was fabricated with e-beam evaporation system in order to measure the modified interface state densities and series resistance. The Schottky barrier height, ideality factor and series resistance of the investigated diode were founded to be 0.81 eV, 1.02 and 21 MΩ respectively at room temperature. I-V parameter was mainly used and the same parameters were determined by performing Cheung and Norde plots. It is evaluated that the series resistance value should be taken into account in determining the interface state density distribution. The founded  $N_{SS}$  value is of the order of  $1.852 \times 10^{13} \text{ eV}^{-1} \text{ cm}^{-2}$  from the forward bias I-V characteristics. This paper describes the detail results of the Cu/Ni Schottky contact formation of thin interfacial layer between the metal and semiconductor at room temperature.

**Index Terms** — InP Schottky contacts, Interface states, I-V Characteristics, Cu/Ni bilayer.

## I. INTRODUCTION

Metal film deposition on indium phosphide (InP) substrates has received much attention for many years because of interest to develop fabrication technology for high speed devices. Schottky barrier contacts based on n-InP are of considerable interest an account of their potential applications in gate electrode of a field-effect transistor (MESFET), microwave devices, high-speed charge-coupled devices and solar cells [1-4]. Schottky contacts play an important role in controlling the electrical performance of semiconductor device and Schottky barrier height (SBH). The SBH is highly sensitive to thermal treatment of the metal-semiconductor interfaces. The development of thermally stable with high barrier height Schottky contacts to InP is one of the main challenges for InP-based device technology. Efforts have been made by several research groups in order to improve Schottky barrier heights [5-7]. Bhaskar Reddy et al. [8] studied the influence of rapid thermal annealing on electrical and structural properties of double metal structure Au/Ni/n-InP diodes. Sankar Naik et al. [9] evaluated the electrical and structural properties of Ni/V Schottky contacts to n-InP after rapid thermal process. They found that the barrier height of the as-deposited Schottky diode was (0.61 eV (I-V) and 0.91 eV (C-V)) high as compared to the annealed contacts. Ashok et al. [10] studied the effect of annealing on electrical and structural properties of Pd/n-InP Schottky contact, and reported that the presence of insulating layer was the responsible for the variation in the barrier heights. Recently, our group investigated the electrical and structural properties of Ru/Ti/n-type InP Schottky structure as a function of annealing temperature [11].

The main aim of the present work is to fabricate double metal structure Ni/Cu Schottky contacts on n-type InP and investigate its electrical properties at room temperature in order to know what happens to metal contacts on InP from a device point of view. Therefore,

we made an attempt to investigate the change in the electrical and interfacial states properties of Ni/Cu/n-InP Schottky diodes.

## II. EXPERIMENTAL METHODS

Liquid Encapsulated Czochralski (LEC) grown undoped n-InP wafer was used in this work and carrier concentration was about  $5.0 \times 10^{15} \text{ cm}^{-3}$ . Before making the ohmic contact, the wafers were initially degreased with warm organic solvents like trichloroethylene, acetone and methanol by means of ultrasonic agitation for 5 min in each step to remove the undesirable impurities and followed by rinsing in deionized (DI) water. The wafer was then dried with high-purity nitrogen and inserted into the deposition chamber immediately after the etching process. Then, the samples were etched with HF (49%) and H<sub>2</sub>O (1:10) to remove the native oxides from the substrate. A metallization scheme of Ni/Cu (300/200 Å) with a diameter of 0.7 mm was deposited on the polished side of the InP wafer through a stainless steel mask under a vacuum pressure of  $5 \times 10^{-6} \text{ m bar}$ . The current-voltage (I-V) characteristics of Ni/Cu Schottky contacts were measured using Keithly source measuring unit (Model No 2400) at room temperature.

## III. RESULTS AND DISCUSSION

The Ni/Cu Schottky diodes have been evaluated using measurements of forward and reverse current-voltage (I-V) characteristics at room temperature. The thermionic emission theory for charge transport in Schottky diodes is used to analyze the data. When a nearly ideal Schottky barrier diode (SBD) is considered, it is assumed that the forward bias current of the device is due to thermionic emission (TE) current and it can be expressed as [16]

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

The saturation current  $I_o$  is determined by extrapolating the linear region of the forward-bias semi-log I-V curves

to the zero applied voltage and the  $\phi_{eff}$  values are calculated from the equation given below.

$$\phi_{eff} = \frac{kT}{q} \ln \left( \frac{A^{**} AT^2}{I_0} \right) \quad (2)$$

Figure 1 shows the typical current-voltage (I-V) characteristics of Ni/Cu Schottky contacts to n-type InP at room temperature. As shown in figure lower one is at 0.05V applied voltage and upper one is at 0.30 V respectively with 0.05 V voltage is varied at every step. The leakage current of the as-deposited Ni/Cu Schottky contact is founded to be  $2.76 \times 10^{-8}$  A at -1 V. Also, the ideality factor n is a measure of conformity of the diode to pure thermionic emission and if n is equal to one, pure thermionic emissions occur. However, n has usually a value greater than unity. The values of n are determined from the slope of the linear region of the forward bias I-V characteristics using the relation [12]

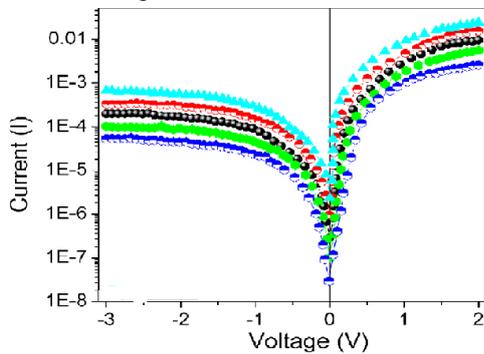


Fig. 1. Current–Voltage characteristics of Ni/Cu/n-InP Schottky contact.

$$n = \frac{q}{kT} \frac{dV}{d(\ln I)} \quad (3)$$

The calculated ideality factor of Ni/Cu Schottky contact is found to be 1.02 at room temperature. This is indicative of non-ideal behaviour, suggesting the transport mechanism, other than just thermionic are probably present in these diodes. The present work observed that the higher values of ideality factor were probably due to the potential drop in the interface layer and the presence of excess current. Another possibility may be attributed to the oxide layer grown on the semiconductor, suggesting that the potential barriers at real metal-semiconductor interfaces depends much more the applied voltage.

The density distribution of the interface states  $N_{SS}$  in equilibrium with the semiconductor can be determined from the forward bias (I-V) data by taking the voltage dependent ideality factor n and barrier height  $\phi_b$  into account. For a diode, the ideality factor n becomes greater than unity as proposed by Card and Rhoderick [1]:

$$n(V) = I + \frac{\delta}{\varepsilon_i} \left[ \frac{\varepsilon_s}{W} + qN_{SS} \right] \quad (4)$$

where  $N_{SS}$  is the density of interface states,  $\varepsilon_s = 11.4 \varepsilon_0$  and  $\varepsilon_i = 3.5 \varepsilon_0$  are the permittivity of the interfacial layer and semiconductor. The value of W was calculated from reverse bias  $1/C^2$  versus V plot as in the following

equations:

$$W = \sqrt{\left( \frac{2\varepsilon_s V_d}{qN_D} \right)} \quad (5)$$

The interfacial layer thickness  $\delta$  is obtained from the C-V data in the strong accumulation region using the equation for interfacial layer capacitance ( $C_i = \varepsilon_i \varepsilon_0 A / \delta$ ) at 1 MHz [72]. The values of  $\delta$  and W are found to be about 16 Å and 1160 Å. Furthermore, in n-type semiconductors, the energy of the interface states with respect to the top of the conduction band at the surface of the semiconductor is given by:

$$E_c - E_{SS} = q(\phi_b - V) \quad (6)$$

Fig.2 shows the energy distribution profile of  $N_{SS}$  as obtained from the forward bias I-V data by using equation (6) of the diode at room temperature. As can be seen in Fig.2, the exponential growth of the interfacial state density is very apparent. The density of interface states of the diode studied is of the order of  $1.852 \times 10^{13} \text{ eV}^{-1} \text{ cm}^{-2}$ . The density of the interface states of the studied diode is lower than that of other literature Schottky

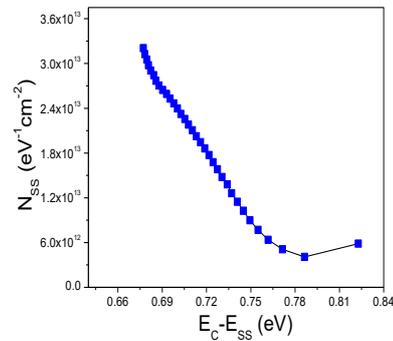


Fig.2. Profiles of interface state density distribution as a function of  $E_c - E_{SS}$ .

contact with a native interfacial insulator layer []. The  $N_{SS}$  values are varied from  $0.6 \times 10^{13} \text{ eV}^{-1} \text{ cm}^{-2}$  to  $3.0546 \times 10^{13} \text{ eV}^{-1} \text{ cm}^{-2}$  as the applied voltage is varied between 0.05 – 3.0 V. Experimental results show that the interface states, interfacial layer play an important role in the determination of barrier parameters of the Schottky devices.

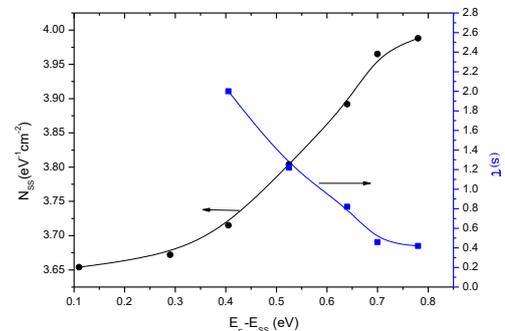
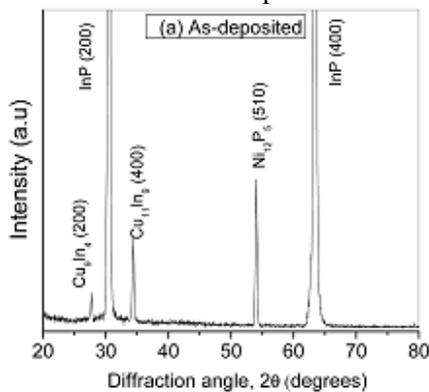


Fig.3. The distribution of the interface state density and their relaxation time constant Vs  $E_C - E_{SS}$ .

Fig.3. shows the experimental  $E_C - E_{SS}$  versus  $N_{SS}$  and  $E_C - E_{SS}$  versus relaxation time,  $\tau$  plot obtained from C-

f characteristics at room temperature. It can be seen from the figure that the interface state densities range from  $0.6 \times 10^{13} \text{ eV}^{-1} \text{ cm}^{-2}$  to  $3.0546 \times 10^{13} \text{ eV}^{-1} \text{ cm}^{-2}$  while the applied voltage varied from 0.05 V to 0.30 V. Besides, the values of the relaxation times range from 2.16 s in 0.65 eV to 0.38 in 0.78 eV. It is seen that the interface state densities increase and the relaxation times show a decrease with bias voltage. At high frequency, the capacitance measured is dominated by the depletion capacitance of the Schottky diode, which is bias-dependent and frequency-independent. As the frequency is increased, the total diode capacitance is affected not only by the depletion capacitance, but also by the bulk resistance and the dispersion capacitance, which is frequency-dependent and associated with hole or electron emission from slowly responding deep impurity levels [12-13]. Because of these effects, the capacitance dependence on bias becomes less pronounced.



**Fig. 4. The XRD plot of the Ni/Cu Schottky contacts on n-type InP**

To identify the interfacial products that are formed at the interface at room temperature, X-ray diffraction (XRD) measurement is used. Fig. 4. shows the XRD plots of the Ni/Cu/n-InP Schottky diodes at room temperature. As shown in Fig., in addition to the characteristic peaks of InP (200) (400), there are other peaks observed, which are identified as  $\text{Cu}_9\text{In}_4$  (200),  $\text{Cu}_{11}\text{In}_9$  (400) and  $\text{Ni}_{12}\text{P}_5$  (510). The formations of other elements are leads to the accumulation of indium vacancies at the InP surface region. This induces an increase in Schottky barrier height of the Ni/Cu contact which is extracted from I-V characteristics and due to reduction of non-stoichiometric defects in the metallurgical interface [16]. The degree of intermixing of In and P with the contact metal and the formation of surface states at the interface are influenced by the chemical reactivity of the metal with InP. The electrical measurements showed that the barrier height is increased with increasing the applied voltage. The improved Schottky barrier height of Ni/Cu contact ascribed to the interfacial reaction occurring between metal layers and InP. Also, the variation of SBHs of Ni/Cu Schottky contact may be due to the observed structural changes in the Ni/Cu contacts on the surface.

#### IV. CONCLUSIONS

The electrical properties of Cu/Ni/n-InP Schottky barrier diode are investigated at room temperature. The barrier height, ideality factor and series resistance of the

diode are determined to be 0.81 eV, 1.02 and 21  $\text{M}\Omega$  from I-V method. Observations reveal that the barrier heights calculated from the Norde method is closely matched with those calculated from the I-V method. As well, the series resistance  $R_s$  of the Ru/Ti/n-InP Schottky diode is determined by Norde method. It is noted that there is a good agreement between the values of the  $R_s$  obtained from Cheung's and modified Norde's method. Besides, under forward bias the I-V characteristic is found to be due to ohmic conduction at low voltage regions, whereas at higher voltage regions due to space charge limited conduction mechanism. The reverse I-V characteristics of Ni/Cu/n-InP reveal that a Schottky emission dominated the reverse current. Thus, results confirm that  $N_{SS}$  and  $R_s$  are significant parameters that influence electrical properties of Schottky barrier contact.

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