Analysis of Electrical Properties and Carrier Transport Mechanisms of Ru/Ti/n-InP Schottky Diodes at Room Temperature

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Abstract: The electrical and current transport mechanisms of the Ru/Ti/n-InP Schottky diodes have been studied at room temperature. I-V and C-V characteristics of the Ru/Ti/n-InP structures are carried out at room temperature. The electrical parameters such as saturation current I_o (1.98×10^{-7}A), ideality factor n (1.19), barrier height ϕ_{bn} (0.82 eV) and series resistance R_s are calculated from I-V data. The ϕ_{bn} and R_s obtained from Cheung's method are compared with modified Norde's method, and it is seen that there is good agreement with each other. Ohmic and space charge limited conduction mechanisms are found to govern the current flow in the Ru/Ti/n-InP Schottky diode at low and high forward bias conditions, respectively. Observation results showed that the Schottky emission is found to be dominant in the reverse bias region of Ru/Ti/n-InP Schottky diode. Moreover, the energy distribution of interface state density (N_{SS}=4.0059×10^{12} $cV^{-1}cm^{-2}$) is determined from the forward bias I-V characteristics by taking into account the bias dependence of the effective barrier height. Finally, it can be concluded that N_{ss} and R_s are significant parameters that control electrical properties of Schottky diode.

Keywords: Ru/Ti/n-InP SD, Electrical properties Interface state density, Series resistance

I: INTRODUCTION

The metal-semiconductor (MS) structures have an important role in modern electronics, and MS structures are one of the most widely used rectifying in the electronics industry [1-5]. Although these devices have been studied extensively, satisfactory understanding in all details but it has still not been achieved. Because there is a continuing need for faster and more complex systems for the information age, existing semiconductor devices are being studied for improvement, and new ones are being invented. Due to technological importance of MS structures, a full understanding of the nature of the electrical characteristics of Schottky barrier diodes (SBD) in this system is of great interest. Indium phosphide (InP) is one of the important semiconductor material for the fabrication of high-temperature, high-frequency and high-power devices due to a direct transition optimum band gap and high-electron mobility [1,2]. However, the studies on Schottky contacts on n-type InP have yielded barrier heights in the range of 0.4-0.55 eV. This may be the chemical reactions and/or out-diffusion occurring on the metal–InP interface produces interfacial layers, which contributes to the barrier by local charge redistribution and/or effective work function change at the interface [3]. As a result, the development of high quality metal-semiconductor (MS) structure is very important since the electrical characteristics of the Schottky barrier diode (SBD) strongly depend on the quality of MS interface. Therefore, the formation of Schottky contacts to InP with high barrier height and low-reverse leakage current is an important research issue in InP device development.

The efforts have been made to improve Schottky barrier heights by several research groups [6-13]. For example, Cetin et al. [6] fabricated Au, Al and Cu Schottky contacts on InP surfaces and they studied the influence of the air-grown oxide on the electrical performance. Reddy et al. [7] investigated the influence of rapid thermal annealing (RTA) on the electrical and structural properties of Pt/Au/n-InP Schottky diode and reported that the maximum barrier height (BH) was obtained (0.51 eV (*I*–*V*)/0.89 eV (*C*–*V*)) for the contact annealed at 300 °C. Also, they found that the formation of intermetallic compounds at the interface may be the reason for the increase of BH after annealing at 300 °C. Huang and Horng et al. [8] fabricated the double layer Pt/Al/n-InP Schottky diodes and studied their electrical and structural properties, and reported that the double metal contact structure provides better rectification characteristics than single metal/n-InP Schottky diodes. Reddy et al. [9] investigated the effect of annealing on the electrical and structural properties Pt/Ti Schottky contacts on n-InP. They found that increase or decrease in the BH upon annealing at elevated temperatures could be attributed to the formation of interfacial phases at the interface. Reddy et al. [10] fabricated the Ni/Cu Schottky rectifiers on n-InP and reported that the BH decreases with annealing temperature compared to the as-deposited one. Also, they reported that the formation of phosphide (P) phases at the interface may be the reason for the decrease in BH upon annealing. Devi et al. [11] studied the electrical and structural properties of Au/Cu/n-InP Schottky diode at different annealing temperature and found that the maximum BH when the contact annealed at 400 °C (0.82 eV (*I*-*V*)/1.04 eV (*C*-*V*)). Naik et al. [12] fabricated Pd/V/n-InP Schottky structure and studied the electrical and structural properties of as a function of annealing temperature. They reported that the increase in BH after annealing at 200 °C may be due to the formation of indium phases at the interface. Recently, Yatskiv et al. [13] prepared Pt/InP junction by electrophoretic deposition of Pt nano particles and studied the electrical properties at different temperatures.

In the present work, our objective is to fabricate and characterize the Ru/Ti double-metal layers on n-InP substrate and investigated its electrical properties at room temperature. A good Schottky contact will induce a large barrier height, which can lead to better device characteristics such as small leakage current and high breakdown voltage. To the best of our knowledge, though many kinds of bilayer schemes are prepared on n-InP as a Schottky contact, Ru/Ti double-metal scheme has not been performed yet. Thus, in this work, titanium (Ti) is selected as first Schottky layer since it has low work function as well as to provide the lowest forward voltage drop. Ruthenium (Ru) is selected as a second layer over Ti contact because it provides a high degree of chemical inertness and also thermal stability since the melting point of Ru is high. In this paper, we report on the electrical properties of Ru/Ti Schottky diode at room temperature using current-voltage (*I*-*V*) and capacitance-voltage measurements. The Schottky barrier parameters of Ru/Ti/n-InP Schottky diode such as barrier height (ϕ_b), ideality factor (n), and series resistance (R_s) have been analyzed. The forward and reverse carrier transport mechanisms have been described and discussed at room temperature.

II: EXPERIMENTAL PROCEDURE

In this study, the Ru/Ti Schottky contacts were prepared on cleaned and polished n-type InP substrate (purchased from Semiconductor Wafer, Inc., Taiwan, thickness: 350 μm). To remove undesirable impurities and surface damage layer, the wafer was chemically cleaned with organic solvents like trichloroethylene, acetone and methanol by means of ultrasonic agitation in sequence for 5 min each, followed by rinsed in deionized (DI) water for 30 s and dried with high-purity nitrogen. Then, InP wafer was etched with HF (49%) and H_2O (1:10) for 60 s to remove the native oxides from the wafer surface and finally the wafer was rinsed in de-ionized water for 30 sec. As well, wafer was dried in N_2 flow. The low resistivity ohmic contact on the backside of InP wafer was formed by deposition of high purity (99.99%) indium (500 Å) metal. Then, the samples were thermal annealing at 350 °C for 60 s in nitrogen ambient in a rapid thermal annealing (RTA) system. After that above procedure, Ti (20 nm) and Ru (30 nm) as first and second layers evaporating as dots on the polished side of the n-type InP with a diameter of 0.7 mm through a stainless-steel mask were deposited using a e-beam evaporation system. An evaporation processes were performed in a vacuum coating unit at a pressure of about 5×10^{-4} pa [9]. The current–voltage (I–V) and capacitance–voltage (C–V) characteristics of Ru/Ti/n-InP Schottky barrier diode was measured using a Keithley source measuring unit (2400) and automated deep level spectrometer (SEMILAB DLS-83D) at room temperature and in the dark, respectively.

III: RESULTS AND DISCUSSION

A) Current-Voltage (V-I) Characteristics

The current–voltage (I-V) characteristics are used widely to study the performance of the Schottky contacts since they offer many important device parameters. Fig. 1 shows the forward and reverse bias curves of the Ru/Ti/n-InP Schottky diode (SD) at room temperature. The reverse leakage current of Ru/Ti/n-InP SD is determined to be 8.835×10^{-10} A at −1 V. The forward-bias current due to the thermionic emission across the Schottky diode with the series resistance (R_s) is given as [9]:

$$I = I_0 \exp\left(\frac{qV - IR_S}{nkT}\right) \quad (1)$$

where saturation current I_o is expressed by:

$$I_0 = AA^{**}T^2 \exp\left(-\frac{q\phi_{bn}}{kT}\right) \quad (2)$$

where q is the electronic charge, T is the measurement temperature in Kelvin, n is the ideality factor, A** is the effective Richardson constant, k the Boltzmann’s constant, R_S the series resistance, ϕ_{bn} is the barrier height and A the contact area. The literature value of A** to n-InP is 9.4 $Acm^{-2}K^{-2}$. Using a linear curve fit to the forward characteristics of ln(I) versus V, the ideality factor n and the barrier height ϕ_{bn} can be calculated. The ideality factor is a measure of the conformity of the diode to be pure thermionic emission and is determined from the slope of the forward bias I-V characteristics (see Fig.1) through the relation:

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

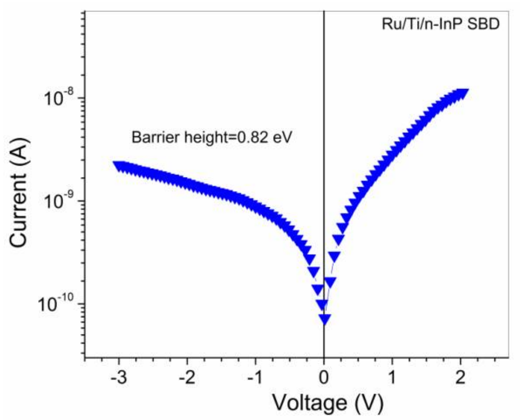

Fig. 1. Typical current–voltage characteristics of the Ru/Ti/n-InP diode at room temperature.

The barrier height ϕ_{bn} can be calculated from the following equation:

$$\phi_{bn} = \frac{kT}{q}\ln\left(\frac{AA^{**}T^2}{I_o}\right) \quad 4$$

The Schottky barrier height (SBH) and ideality factors of the Ru/Ti/n-InP SD are obtained as 0.82 eV and 1.19, respectively. The ideality factor calculated is larger than unity, which is ascribed to secondary mechanisms that include interface dipoles due to interface doping as well as fabrication–induced defects at the interface [14-16]. Other reason may be due to the presence of a wide distribution of low-SBH patches caused by laterally barrier inhomogeneity [16]. Furthermore, the image-force effect, recombination-generation, and tunneling may be possible mechanisms which could lead to an ideality factor greater than unity [16]. Further, the series resistance (R_s) and shunt resistance (R_{sh}) of the Ru/Ti/n-InP SD can be found by plotting the junction resistance against applied voltage as shown in Fig. 2. The values of series resistance, R_S and shunt resistance R_{Sh} are determined as 260 MΩ and 1.2934×10^{10} Ω respectively.

Usually, at low voltages the forward bias current–voltage (I–V) characteristics are linear in the semi-logarithmic scale but deviate significantly from linearity due to the effect of series resistance and interface state density when the applied voltage is sufficiently large. The values of barrier height (ϕ_{bn}), ideality factor (n) and series resistance (R_S) can be calculated precisely using the method developed by Cheung [17]. The Cheung's functions are given as:

$$\frac{dV}{d(\ln I)} = IR_S + n\left(\frac{kT}{q}\right) \quad 5$$

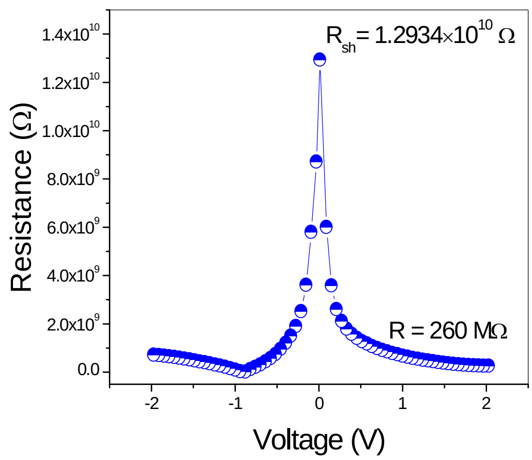

Fig. 2. Plot of the junction resistance between Ru/Ti and n-InP versus voltage at room temperature.

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{1}{AA^{**}T^2}\right) \quad 6$$

and $$H(I) = IR_S + n\phi_b \quad 7$$

should give a straight line for the data of non-linear (downward curvature) region in the forward bias I–V characteristics. The experimental dV/d(ln I) versus I, and H(I) versus I plots for the Ru/Ti/n-InP Schottky diode are shown in Fig. 3. The values of ideality factor (n) and Series resistance (R_s) are found to be 1.24 and 45 MΩ from the dV/d(ln I) versus I plot. A plot of H(I) versus I based on Eq. (6) will also give a straight

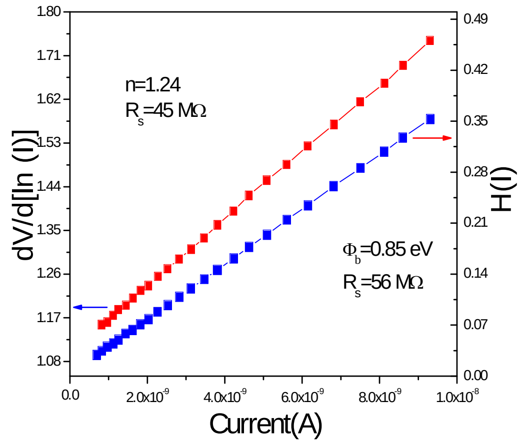

Fig. 3. Plots of dV/d(lnI) versus I and H(I) versus I for Ru/Ti/n-InP Schottky barrier diode.

line. The slope of this plot provides a second determination of Rs, which can be used to check the consistency of Cheung's approach. Thus, by using the value of the ideality factor obtained from Eq. (5), the value of barrier height (ϕ_{bn}) can be calculated from the y-axis intercept of the H(I)-I plot. From H(I) versus I plot, ϕ_{bn} and R_S are calculated as 0.85 eV and 56 MΩ respectively. The calculated values of R_s from the plots of dV/d(lnI) versus I are identical to those from the plots of H(I) versus I, implying their consistency and validity.

The Schottky barrier height ϕ_{bn} and series resistance (R_S) of Ru/Ti/n-InP SD can also estimate by the modified Norde's function [18] and is defined as

$$F(V)=\frac{V}{\gamma}-\frac{1}{\beta}\ln\left[\frac{I(V)}{AA^{**}T^2}\right] \quad 8$$

where γ is the integer greater than ideality factor, I(V) is the current obtained from the I-V curve and β is a temperature dependent value calculated using β=q/kT. The effective ϕ_{bn} is given by

$$\phi_{bn}=F(V_0)+\frac{V_0}{\gamma}-\frac{kT}{q} \quad 9$$

where $F(V_0)$ is the minimum point of F(V) and V_0 is the corresponding voltage. The Norde function F(V) versus V plot for the Ru/Ti/n-InP Schottky barrier diode is shown in Fig. 4. Norde function describe the series resistance as

$$R_S=\frac{kT(\gamma-n)}{qI_{min}} \quad \mathbf{10}$$

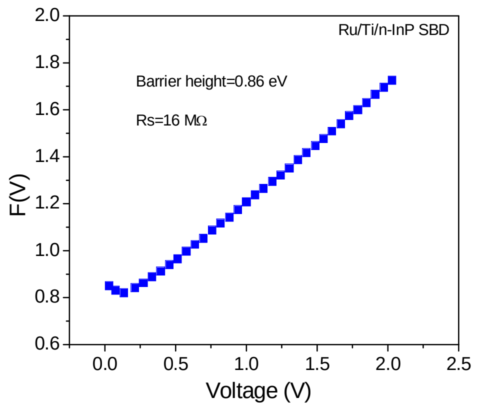

Fig. 4. Modified Norde plot of the Ru/Ti/n-InP Schottky barrier diode obtained from forward I-V characteristics.

The ϕ_{bn} and R_S values are determined from the modified Norde plot as 0.86 eV and 16 MΩ respectively. The values of ϕ_{bn} calculated from the Norde function is in good agreement with the value obtained from I-V characteristics and Cheung's functions. Besides, the series resistance estimated from the Norde function is comparable with those estimated from the plots of dV/d(lnI) versus I and H(I) versus I. Furthermore, the values of R_S indicated that the R_S is a current-limiting factor for this structure. The effect of the R_S is usually modelled with series combination of a diode and a resistance. The voltage drop across a diode is determined in terms of the total voltage drop across the diode and the resistance.

The current conduction mechanism dominating in the forward bias region of the Ru/Ti/n-InP Schottky barrier diodes, a forward bias log I-log V plot is presented in Fig. 5. The present investigated Schottky barrier diode reveals three distinct regions under forward bias which are called as region I, II and III as shown in Fig. 5. These three linear regions have different slopes that obey IαV^m change, here m is the slope of the plot for each linear region and the values are found to be 0.5590, 1.2713 and 2.0665 respectively. In the region I, the current conduction mechanism exhibits an ohmic behaviour at low bias region, which is due to existing background doping or thermally generated carriers. In the region II, the Ru/Ti/n-InP Schottky diode can be characterized by power law dependence, indicating the charge transport is governed by space charge limited current (SCLC) with a discrete trapping level. The value of slope is about 2.0665 for the Ru/Ti/n-InP Schottky diode in the region III. The slope of the plot at high voltages tends to decrease since the device approaches the "trap-filling" limit when the injection level is high whose dependence is the same as in the trap-free SCLC [19].

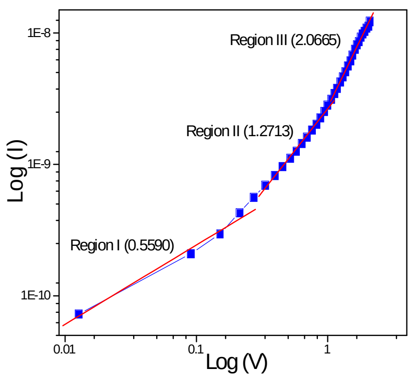

Fig. 5. The forward bias log (I) versus log (V) plot of the Ru/Ti/n-InP Schottky barrier diode.

The Poole-Frenkel and Schottky barrier lowering mechanisms across the junction is employed in order to analyze reverse leakage current mechanism. The plots of Poole-Frenkel emission (I_R/E versus E$^{1/2}$) and Schottky emission (I_R/T^2 versus E$^{1/2}$) are shown in Fig. 6. The plots of I_R /E versus E$^{1/2}$ and I_R/T^2 versus E$^{1/2}$ produce a linear curve and their slope can be expressed as [20]:

$$S = \frac{q}{nkT}\sqrt{\frac{q}{\pi\varepsilon}} \qquad \textbf{11}$$

where n=1, 2 for the case of Poole–Frenkel and Schottky emission, respectively. The theoretically calculated slopes obtained from the fits for both Poole–Frenkel emission and Schottky emission are 0.00953 and 0.00477 (V cm^{-1})$^{-1/2}$, respectively. The slope determined from the plot of I_R/E versus E$^{1/2}$ (Fig. 6) is 0.00324 (V cm^{-1})$^{-1/2}$ which is smaller than the theoretical value for Poole-Frenkel emission. This indicates the absence of the Poole–Frenkel mechanism in the Ru/Ti/n-InP Schottky barrier diode. On the other hand, the slope determined from the plot of I_R/T^2 versus E$^{1/2}$ (Fig. 6) is 0.00433 (V cm^{-1})$^{-1/2}$ which closely matched with the theoretical value of Schottky emission. Therefore, the results indicate that the Schottky emission is a dominant conduction mechanism in Ru/Ti/n-InP Schottky barrier diode. In this mechanism, the thermally-activated carriers are emitted over the metal–semiconductor barrier under the influence of the electric field which lowers the barrier height.

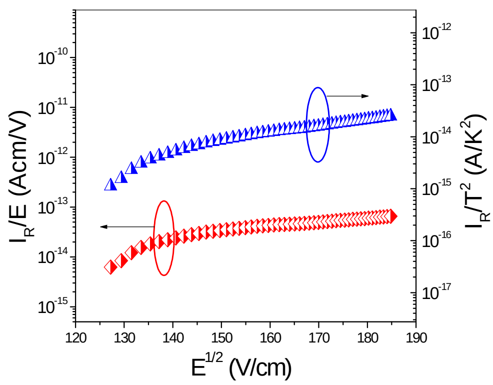

Fig. 6. Plot of I_R/E versus E$^{1/2}$ and I_R/T^2 versus E$^{1/2}$ for the Ru/Ti/n-InP Schottky diode.

B) Capacitance–Voltage (C-V) Characteristics

The capacitance-voltage relationship for Schottky diode is given by [1]:

$$\frac{1}{C^2} = \frac{2(V_R + V_d)}{q\varepsilon_s N_D A^2} \qquad \textbf{12}$$

where ε_s=11.4ε_0 is the permittivity of the semiconductor, ε_0=8.85×10^{-14} F cm^{-1} is the vacuum dielectric constant, V_R is the reverse bias voltage, V_d is the diffusion potential, and N_D is the doping concentration. The measurements of the capacitance C of the samples are realized at 1 MHz. Fig. 7 shows the 1/C^2 versus V characteristics of the Ru/Ti/n-InP SD. The barrier height from C–V measurement is defined by:

$$\phi_{bn} = V_d + \frac{kT}{q} + \phi_n \qquad \textbf{13}$$

where ϕ_{bn} is the Fermi energy measured from the conduction band.

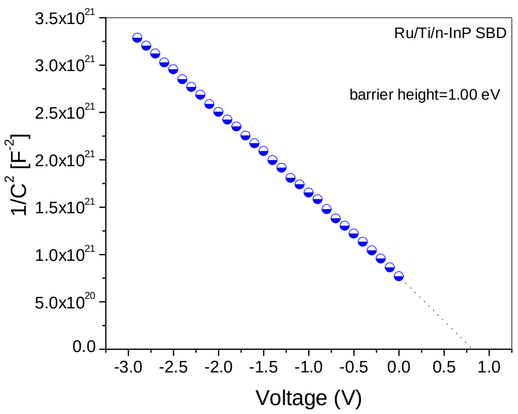

Fig. 7. Plot of 1/C^2 versus V of the Ru/Ti/n-InP Schottky barrier diode.

The diffusion potential or built-in potential at zero bias is usually measured by extrapolating C^{-2} versus V plot to the x-axis (see Fig. 7). For the Ru/Ti/n-InP Schottky diode, the calculated doping concentration N_d and the barrier height ϕ_{bn} are 2.42×10^{19} cm^{-3} and 1.00 eV, respectively. The parameters determined from I–V and C-V characteristics of Ru/Ti/n-InP Schottky diodes are given in Table 1. The present work shows the barrier heights estimated from I–V measurements are considerably lower than those estimated from C–V measurements. This indicates that the current in I–V studies is dominating by the current which flows through the region of low Schottky barrier height (SBH). Also, the observation made that I–V barrier height is significantly lower than the weighted arithmetic average of the SBHs. Consequently, the barrier height estimated by C–V is close to the weighted arithmetic average of the SBHs [5,9,12,21].

Table 1. Calculated parameters of the diode

Parameter	Ru/Ti/n-InP
Schottky Barrier Height from I-V	0.82 eV
Ideality factor (n)	1.19
Schottky Barrier Height from C-V	1.00 eV
Series Resistance (from Norde method)	16 MΩ
Interface States Density (N_{ss}) eV^{-1}cm^{-2}	4.0059×10^{12}
Series Resistance, R_S (from I-V method)	260 MΩ
Shunt Resistance, R_{sh}	1.2934×10^{10} Ω

C) Determination of Interface States Density (N_{SS})

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 ϕ_{bn} into account. For a diode, the ideality factor n becomes greater than unity as proposed by Card and Rhoderick [22]:

$$n(V) = I + \frac{\delta}{\varepsilon_i}\left[\frac{\varepsilon_S}{W} + qN_{SS}\right] \qquad \textbf{14}$$

where N_{ss} is the density of interface states, ε_s=11.4 ε_o and ε_i =3.5 ε_o 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:

$$W = \sqrt{\left(\frac{2\varepsilon_S V_d}{qN_d}\right)} \qquad \mathbf{15}$$

The interfacial layer thickness δ 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 [21]. The values of δ 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:

$$E_c - E_{SS} = q(\phi_{bn} - V) \qquad \mathbf{16}$$

Fig. 8 shows the energy distribution profile of N_{ss} is obtained from the forward bias I-V data by using Eq.(14) of the diodes at room temperature. As can be seen in Fig. 8, 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 4.0059×10^{12} cm^{-2} eV^{-1}. The density of the interface states of the studied diode is lower than that of other literature Schottky diodes with a native interfacial insulator layer [23]. Experimental results show that the interface states, interfacial layer play an important role in the determination of barrier parameters of the Schottky devices.

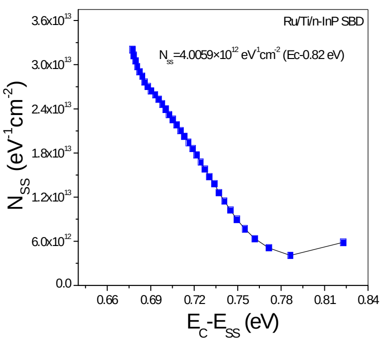

Fig.8. Profiles of interface state density distribution as a function of E_c-E_{SS} (eV).

IV: CONCLUSIONS

The electrical properties and carrier transport mechanisms of Ru/Ti/n-InP Schottky barrier diode are investigated. The barrier height, ideality factor and series resistance of the diode are determined to be 0.82 eV, 1.19 and 260 MΩ 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 Ru/Ti/n-InP SD reveal that a Schottky emission dominated the reverse current. The interface state density of the Ru/Ti/n-InP SD is 4.0059×10^{12} eV^{-1} cm^{-2}. Results confirm that N_{ss} and R_s are significant parameters that influence electrical properties of Schottky barrier diode.

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