Laterally inhomogeneous barrier analysis of cu/n-gap/al schottky devices

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Abstract. In this study, we examined the electrical parameters of Cu/n-GaP/Al Schottky structures at room temperature and examined the electrical characterization of these devices depending on and Capacitance-Voltage (C-V) and Current-Voltage (I-V) measurements. A statistical study on the experimental ideality factor (n) and BHs(barrier heights) values of the devices was stated. The n and BHs of all contacts have been determined from the electrical characteristics. Even though all of the diodes were conformably prepared, there was a diode-to-diode variation: the effective BHs changed from 0.988-0.07 to 1.216-0.07 eV, and the n from 1.01-0.299 to 2.16-0.299. The yielded results show that the mean electrical parameters of Schottky devices are different from one diode to another, even if they are identically prepared.It can be axplained that the lower BHs usher with the higher n values owing to inhomogeneities.

1. Introduction

InP compound is the first of III-V group compounds. Then, binary compounds between (III-a) with (V-a) group elements were formed by Huggens. In 1929, GaP, InSb, GaAs, GaSb, AlAs, AlSb, AlP and AlN compounds were performed by Hilsum [1]. III-V group compounds gained importance as a new family of semiconductors because of their small energy gap, direct band structure and high electron velocity. Superior circuit elements non-existing in Si circuit elements were achieved by using these semiconductors. Advanced technological devices were obtained by using these circuit elements. Additionally, the effects of dislocations on the electronic and interface states of Schottky devices based III-V semiconductor have been examined. Arrivals provided in circuit elements as diode, transistors gained great contributions to semiconductor technology and integrated circuit technology have been developed with the studies performed in this area [2]. GaP (III-V semiconductor) has a great potential for electronic circuit applications owing to wide and indirect band gap (2.26eV at room temperature) [3] and high ionization energy level.

GaP Schottky diodes can be used as opto-electronic circuit elements such as high efficiency detectors and LED (light emitting diode) in GaP Schottky technology The electronic parameters can be determined by different methods. The proceeding developments in GaP Schottky technologies in the production of high efficiency detector and LED's (light emitting diodes) have played an important role more researches and in the determination of their electronic parameters about MS and MIS structures. Electronic parameters can be determined by different methods. The most frequently used of these are the measurement methods with (I-V) and (C-V).

GaP (Gallium phosphide) has an indirect band gap (2.26eV) with the cubic crystal structure which are diamond and zinc blende. Yet, it has direction band gap with hexagonal (wurtzite) crystal structure when the band gap of this material changed [4]. GaP's lattice constant is calculated as 5.45 Å [5]. GaP semiconductor consists of the combination of the III groups G and the V groups P elements. Crystal structure of GaP is zinc sulphide (zinc blend) [4] structure. The only difference from the diamond structure of the zinc sulphide structure is diatomic and is a structure observed in semiconductors with two atoms. Electrical properties and growth of GaP semiconductor has attracted a lot of attention by scientists in recent years. GaP semiconductors grow with many techniques such MBE (Molecular Beam Epitaxy) [6], Liquid Phase Epitaxy [7], RF-Magnetron Sputtering [8] and Chemical vapour deposition [9]. Blank *et al.* Reported that single crystal n-GaP (100) deposited with Czochralsky method and it has properties such as n = (2–4) × 10^{17} cm^{-3} and μn = 100– 110 cm^2 V^{-1} s^{-1} (300 K). The dislocation density was P_d ~ 10^6 cm^{-2} in crystals [10].

In recent years, electronic based on semiconductor materials has been made great progress. Semiconductor technology has entered into every phase of our daily live. For this reason, determination of the electrical and optical properties of semiconductor materials of all kinds will contribute to the expansion of the usage fields of these materials.

The preparation and production methods of the circuit elements produced from these materials and semiconductor materials have a significant influence on the electronic properties and parameters of these materials. The electronic industry is the basis of the electronic or opto-electronic devices obtained by using semiconductor crystals. The structure of these devices which are very small sizes, electrical characteristics and determination of operating conditions is very important in terms of the performance and of reliability these devices. Therefore, the examination of the electrical properties of metal-insulating-semiconductor (MIS), metal-oxide –semiconductor structures (MOS) and metal-semiconductor (MS) has gained importance. The parameters that affect the performance of such structures are the thickness and homogeneity of the insulating oxide layer, the series resistance of the structure, interfacial states, the homogeneity of the potential barrier formed between metal and semiconductor.

Semiconductor materials are being constantly investigated until today. In recent years, MS and MIS contacts have been heavily used in the semiconductor and optoelectronic technologies. High quality electronic and opto-electronic devices have been developed as a result of these researches. These devices have the wide application facilities in opto-electronic, integrated circuits, light and ultraviolet (UV) detectors, solar cells, defense and space technology.

In general, theoretical understanding of metal-semiconductor contacts has been after technological development. The most of the theoretical developments have been reviewed by scientists concerned with metal-vacuum systems. Initially, image force barrier lowering has been found owing to the electric field applied in metal-vacuum system. However, this was experimentally confirmed much later in MS system. Afterward, thermionic emission describes for electrons emitted into vacuum from the hot metal. This event demonstrates that can be applied to MS rectifiers, also.

Schottky has revealed the first time that a potential barrier has occurred in the interfacial of MS. Therefore, it is called Schottky diodes or Schottky contacts to MS contacts [11]. In the model developed by Schottky, electric field being in semiconductor increases linear with distance from depletion layer according to Gauss's law and potential decreases. Mott developed another a model associated with potential barrier. Mott adopted that a thin layer is in near of metal-semiconductor [11]. The electric field of this layer remains constant but potential varies linearly. According to Mott, potential barrier arises from the difference between the work functions of MS. Crowell and Size integrated the thermionic emission theory of Bethe and the diffusion theory of Schottky describing the current transmission mechanisms in MS contacts [12].

The first study on insulating layer between MS in Schottky contacts was studied by Cowley and Sze. They analyzed to Schottky BH with different metals [13]. Furthermore, many surface states in interfacial of semiconductor/oxide layer in the metal-semiconductor junction consist of depending on the oxidation process and thermal processes a disorder arising from the crystal structure during cleaning of crystal [14-15]. Card and Rhoderick discussed the intensity of the situation in interfacial and examined to effect of interfacial conditions on n calculated from forward bias I-V characteristics[16]. Tseng and Wu examined to effect on the behaviour of Schottky diode from forward bias I-V characteristics and the distribution of interfacial state densities in semiconductor energy-band gap in the existence of interfacial oxide layer [17]. There are numerous experimental and theoretical methods to obtained interfacial state densities and these methods have their own advantages and disadvantages [18]. However, the most practical and the fastest thing of them is the forward bias I-V method. This method contains a lnI-V plot that n and the potential BH changed to depend on the voltage [19-20].

In this work, our purpose is to experimentally examine the relationship between the effective BHs and n obtained from the forward bias I-V and reverse bias C-V characteristics of the Cu/n-GaP/Al Schottky devices at room temperature. The homogeneous BH value for the diode was yield from the linear relationship between the experimental effective ns and BHs. The characteristics of the Schottky diodes must be very well known for the correct and efficient use. The operation and reliability of these diodes depend on the characteristics and shaping of the insulating layer between MS, the distribution of surface states in semiconductor-insulator, homogeneity of contact. All of them are very important properties causing deviations from the the ideal situation of semiconductor device and should be considered in the calculations. The inter of metal-semiconductor may not be always ideal in Schottky contacts. Thus, a parameter called n takes place in characteristics at this stage. Ones can get knowledge about the properties of the structure to examination the capacity of contact region in metal-semiconductor contacts. The essential parameters such as the potential BH of the structure, built-in potential, carrier density can be determined with help I-V and C-V measurements of Schottky diodes. The statistical distribution of the characteristics of these structures was made with the Gaussian function.

2. Experimental

In this work, we used one side polished n-GaP samples. We have prepared Cu/n-GaP/Al Schottky diodes on n-GaP semiconductor with the thickness of 400 μm and carrier density of $2.4x10^{16}$ cm^{-3}. Initially, semiconductor samples were cleaned (with processes such as i. each sample was waited for 5 min using trichloroethylene, acetone and methanol and they were immersed into DI water, ii. samples were waited in $3H_2SO_4 + H_2O_2 + H_2O$ for 60 second and rinsed with DI water, iii. they were waited in $HF:H_2O$ (1:10) for 30 second and rinsed with DI water, then dried with unreacted nitrogen) [21]. Al metal was prefered to create ohmic contact on the back surface of the semiconductor sample in Univex-300 Pump system with a pressure of $4x10^{-5}$ Torr and then annealed under N_2 gas flow at 500°C for 3 minutes [22]. Schottky diode was fabricated by evaporation using Cu metal on the front surface of GaP wafers. A turbo molecular vacuum coating unit at about 10^{-6} mbar pressure were carried out the processes of evaporation. A Keithley 487 picoammeter device was used to measure the I-V characteristics of contacts and HP-4192 an impedance analyser used to obtain the C-V measurements at 100kHz, also.

3. Results obtained

Figures 1 shows the XRD patterns of the GaP The XRD measurements revealed the peaks corresponding to the GaP crystal planes of (200) and (400), by JCPDS files (The Joint Committee on Powder Diffraction Standard), indicating the polycrystalline nature of the sample. FWHM and grain size values of GaP(200) and GaP (400) directions were calculated as (0.0558-0.0883), (1490-1090), respectively. Figure 2 indicates both forward and reverse bias log (I-V) plot of Cu/n-GaP/Al Schottky. A statistical distribution on the experimentally BHs and n values of the devices was formed. The n and BHs of all contacts have been yielded from the electrical characteristics. Although the diodes were all identically prepared, there was a diode-to-diode variation: the effective BHs changed from 0.988-0.07 to 1.216-0.07 eV, and the n from 1.01-0.299 to 2.16-0.299.

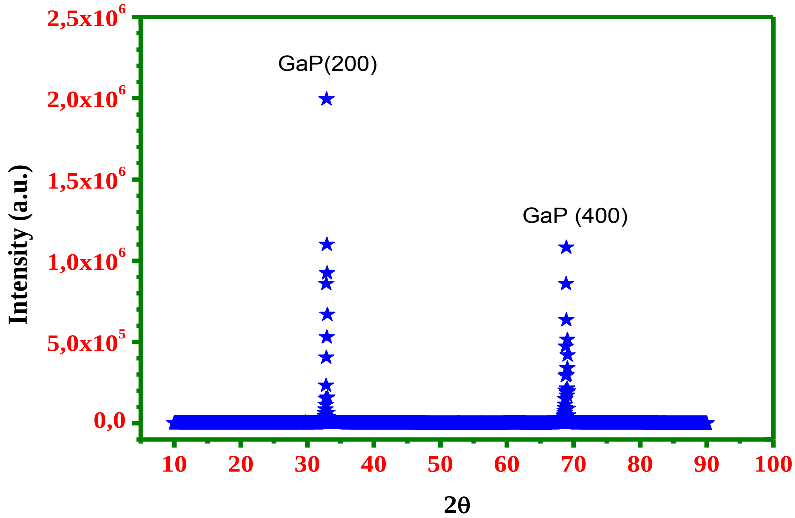

Figure 1. The XRD measurements of the n-GaP

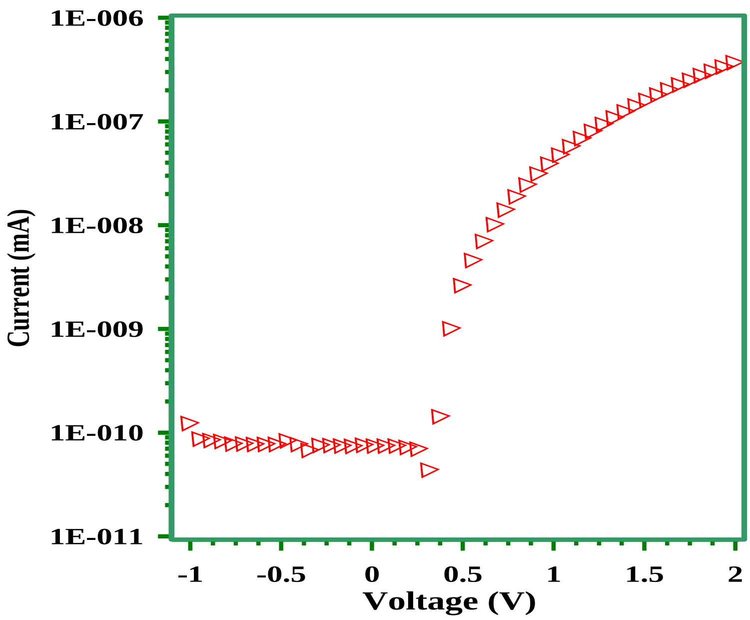

Figure 2. Forward and reverse bias log (I-V) plots of Cu/n-GaP/Al Schottky diode

It is estimated in MS devices that the current flow through a diode can be determined by thermionic emission (TE) theory as follows;

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

where q is the electronic charge, k Boltzmann constant, T temperature, V the applied voltage, which is given by:

$$n = \frac{q}{kT}\left(\frac{dV}{d(\ln I)}\right) \quad (2)$$

I_0 is the reverse saturation current which is obtained from the straight line intercept of $\ln I$ at $V = 0$ in Eq. (1) and is given:

$$I_0 = A^* A T^2 \exp\left(-\frac{q\Phi_{b0}}{kT}\right) \quad (3)$$

where A^* is the effective Richardson constant, A the diode area and Φ_{b0} the zero-bias BH. A* is the effective Richardson constant and is equal to 98.2 $Acm^{-2}K^{-2}$ for n-GaP. ε_s is the dielectric constant of semiconductor and is equal to 10.75 for n-GaP [21], [23] and A, the diode area, is 1.963×10^{-3} cm^2. The density of states in the conduction band is $N_c=1.27\times10^{19}$ cm^{-3} for the calculation of contact parameters.
The basic *C-V* evaluation with respect to the semiconductor in-depth doping profile is based on the depletion approximation. Rhoderick stated to the capacitance of the space charge region within the depletion approximation [24]:

$$C = \frac{|\partial Q_{SC}|}{\partial V} = \sqrt{\frac{q\varepsilon_s N_D}{2(V_{bi} - V - kT/q)}} = \frac{\varepsilon_S}{W} \quad (4)$$

This equation can also be written as:

$$\frac{1}{C^2} = \frac{2(V_{bi} - V - kT/q)}{q\varepsilon_S N_d} \qquad (5)$$

or

$$-\frac{d(1/C^2)}{dV} = \frac{2}{q\varepsilon_S N_d} \qquad (6)$$

The capacitance of the space charge region provides important information about the metal/semiconductor interfacial in Schottky contacts. Elements such as the BH of rectifier contact, carrier concentration of the semiconductor, built-in potential (V_{bi}) which is obtained from intercept of $1/C^2$ -V plot on bias axis and the Fermi level are assigned from capacitance depending on the change in voltage at reverse bias:

$$N_d = \frac{2}{q\varepsilon_S}\left[-\frac{1}{d(1/C^2)/dV}\right] \qquad (8)$$

Where Nd is the ionized donor concentrations, and if Nd is constant throughout the depletion region, it can be made to fit the $1/C^2$ -V plot. The SBH for semiconductor is given by:

$$\Phi_B(C-V) = V_{bi} + E_f \qquad (9)$$

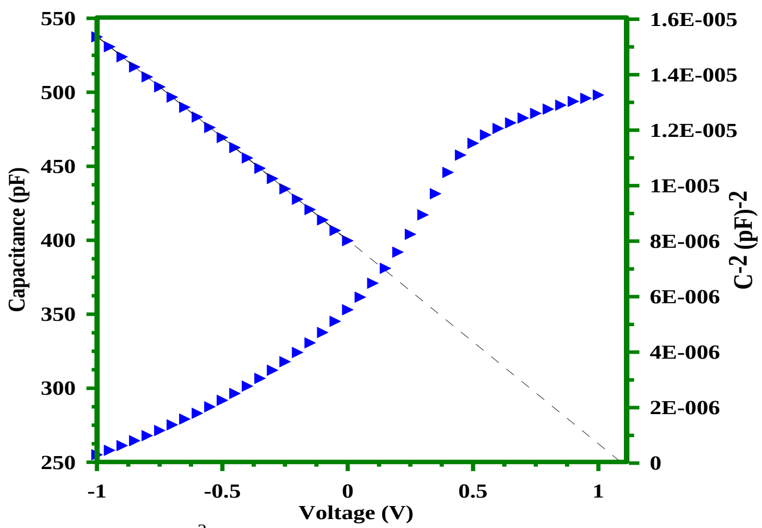

Figure 3. C-V and C^{-2}-V plots of Cu/n-GaP/Al Schottky diode at 100 kHz

Figure 3 demonstrates C-V and C^{-2}-V plots of Cu/n-GaP/Al Schottky diode. Built-in potential, BH, Fermi level and donor concentration values of Cu/n-GaP/Al Schottky contacts were obtained with the help of these curves. The values of these parameters were obtained as 1.094 eV, 1.180 V, 0.085eV and 4.639×10^{17}cm^{-3} at 100 kHz, respectively.

Figure 4 indicates to the distribution of the ns obtained from the forward bias I-V characteristics of the Cu/n-GaP/Al Schottky devices. As shown, the Gaussian fit provides a mean n value of 1.30 with a standard deviation of 0.29. Figure 5 demonstrates the statistical distribution of BHs from forward bias I-V plots of the Cu/n-GaP/Al Schottky devices. And Figure 6 indicates the statistical distribution of BHs from the $(1/C)^2$-V plots of the same diodes. The experimental distribution of the effective BHs were fitted by the Gaussian function. At first, let us consider the I-V BHs. The statistical analysis obtained a mean BH value of 1.11 eV with a standart deviation of 0.069 eV. The distribution of the BHs obtained from the $(1/C)^2$-V curves of the Cu/n-GaP/Al Schottky diodes at 100 kHz. The statistical analysis obtained a mean BH value of 1.19 eV with a standart deviation of 0.029 eV. The statistical distribution of donor concentration values from the $(1/C)^2$-V plots of the same diodes is showed in Figure 7. The statistical calculations provided a mean donor concentration value of 4.278×10^{17} cm^{-3} with a standart deviation of 4.59×10^{16} cm^{-3}.

n, low series resistance and low reverse bias current values are important for the realization of the Schottky diodes. It is cleared as ideal diode that n is 1 at Schottky diode. The I-V characteristics of Schottky contacts do not only provide any knowledge regarding to the charge transport, but gives information relevant to the barrier formed in the MS interfacial. The electronic properties of Schottky barrier diode are determined by n and BH. The difference of BH on contacts changes with the thickness of the interfacial layer, the charge density in the interfacial layer, the oxidation of the semiconductor surface, the formation of the pollution atoms collected metal, the temperature and the radiation [25].

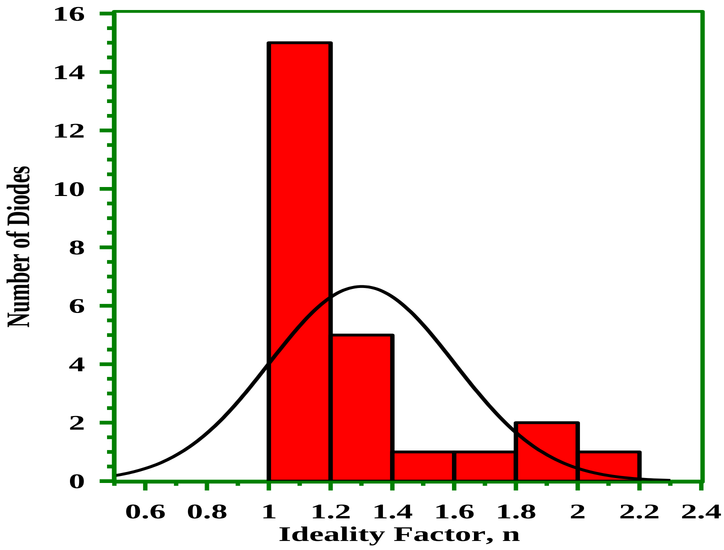

Figure 4. Gaussian distribution of n from the I–V characteristics of the Cu/n-GaP/Al Schottky structures

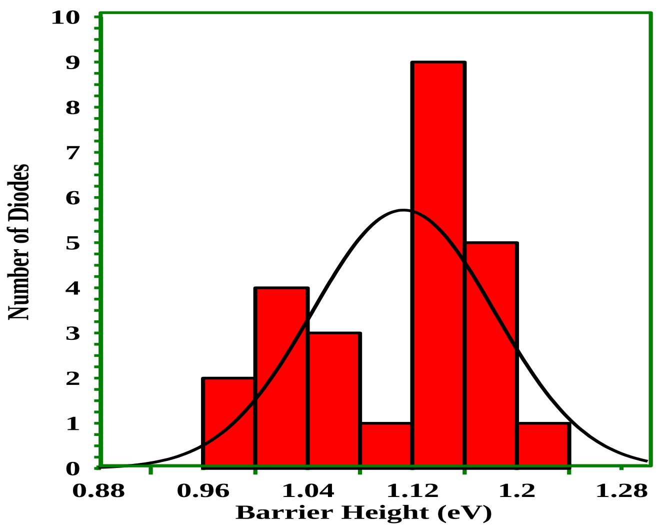

Figure 5. Gaussian distribution of BHs determined from the I–V characteristics of the Cu/n-GaP/Al Schottky structures

The BH obtained from I-V measurements is typically less than these from *C-V* measurements. The reason for this is arised from the difference in measurement methods. Furthermore, the many elements such as contaminants in interfacial, quantum mechanical tunnelling, leakage currents, image force decreasing and deep impurity levels focused on this difference [14], [26]. It can be stated by the presence a thin layer compensated in interfacial [27].

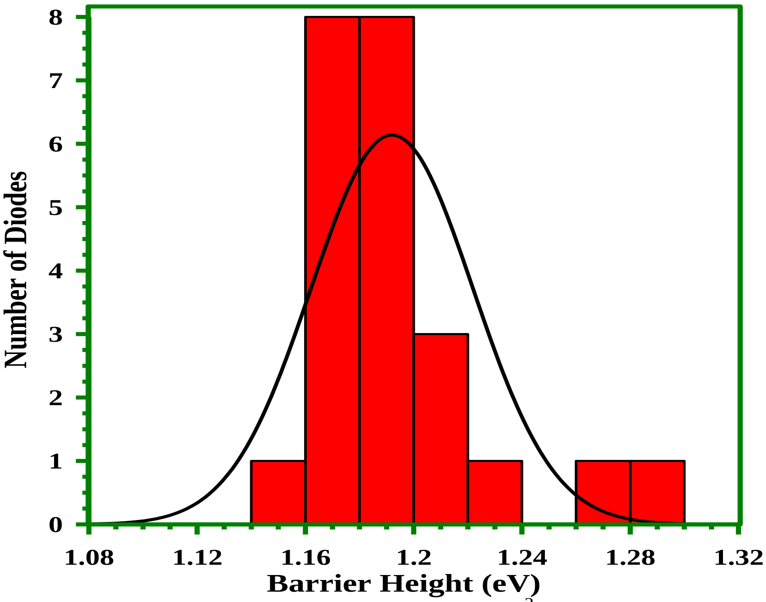

Figure 6. Gaussian distribution of BHs obtained from the C^{-2}-V characteristics of the Cu/n-GaP/Al Schottky structures

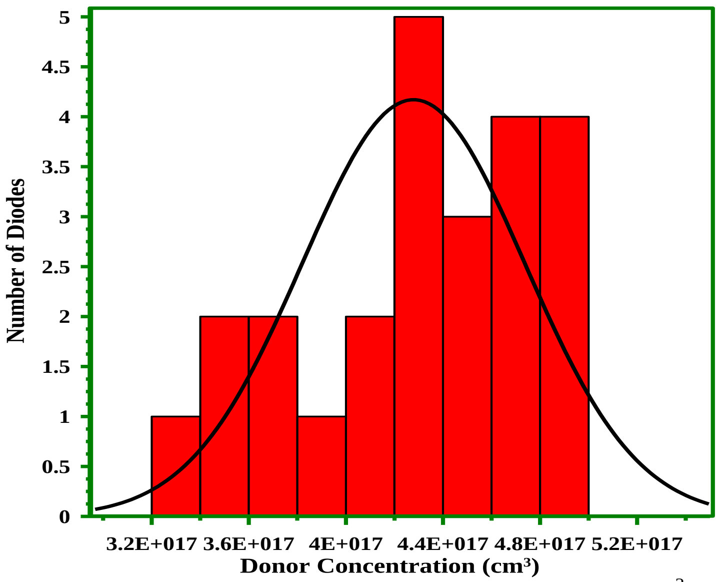

Figure 7. Gaussian distribution of donor concentration yielded from the $1/C^2$–*V* characteristics of the Cu/n-GaP/Al Schottky structures

Cheung *et al*. reported that the series resistance values of Schottky devices can be obtained depending on TE theory [28];

$$I = AJ = \left[AA^* T^2 \exp\left(\frac{-e(\Phi_B - IR_s)}{kT} \right) \right] \cdot \left[\exp\left(\frac{e(V - IR_s)}{nkT} \right) \right] \tag{10}$$

where the IR_s term is the voltage drop across series resistance of diode. The values of the series resistance can be calculated from the following functions using eq. (10);

$$\frac{dV}{d\ln(I)} = \frac{nkT}{e} + IR_s \tag{11}$$

and H(I) is given as follows;

$$H(I) = V - \frac{nkT}{e}\ln\left(\frac{I}{AA^*T^2}\right) \tag{12}$$

$$H(I) = n\Phi_B + IR_s \tag{13}$$

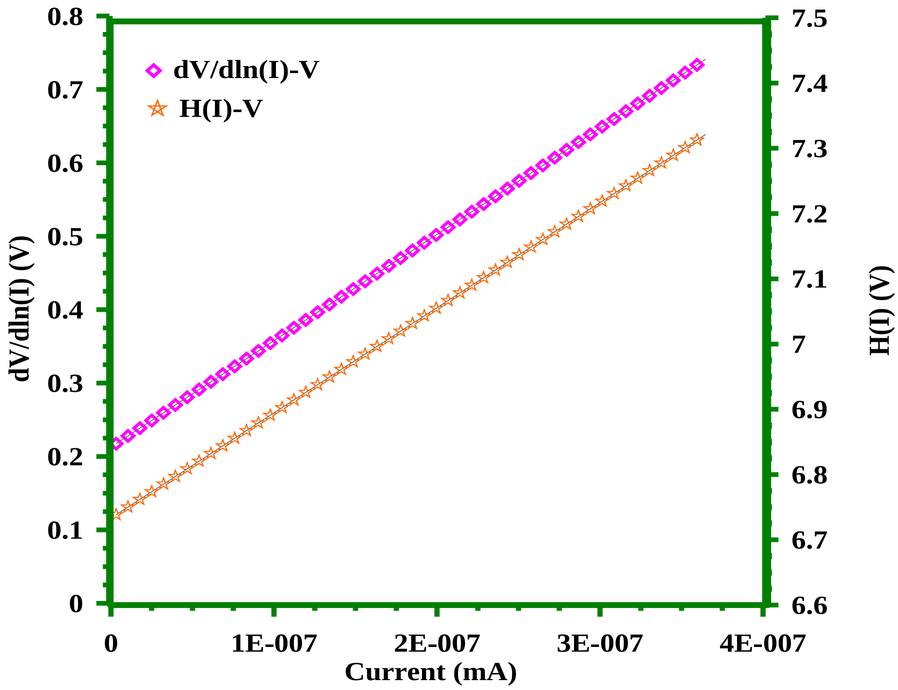

Figure 8. dV/dln(I) and H(I) vs. Voltage curves of Cu/n-GaP/Al Schottky diode

As shown Figure 8, series resistance, BH and n parameters of Cu/n-GaP/Al Schottky device were calculated with the help the slopes of the dV/dln(I) and H(I) versus voltage curves. n and series resistance values obtained from the dV/dln(I) versus voltage plots are 8.22 and 1148 kOhm. Also, the series resistance and BH values with the help of H(I) versus voltage plots were calculated as 1611 kOhm and0.819 eV, respectively. Semiconductor crystal surfaces used in semiconductor devices have usually organic soils and the natural oxide layer in a laboratory environment. The natural oxide layer in the cleaned semiconductor surfaces occurs chemically with exposure to the clean room air of semiconductor [29]. Thickness of the insulating layer between metal-semiconductor depends on chemically residual gases on the cleaned material and duration of exposure to the environment of semiconductor surface. The presence of this insulating layer affects the basic diode parameters such as surface states, Schottky BH, n and series resistance [30], [16].

Figure 9 shows the Cu/n-GaP/Al plot obtained with Norde method. Bohlin proposed using the modified Norde method as another way to find the Schottky contact parameters, in which its method is given as[31];

$$F(V) = \frac{V}{\gamma} - \frac{kT}{e} In\left(\frac{I(V)}{AA^*T^2}\right) \tag{14}$$

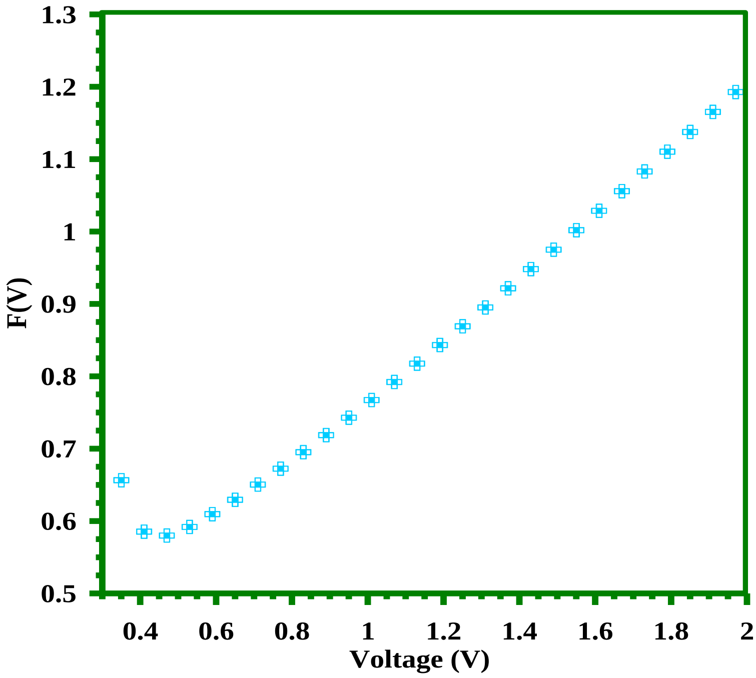

Figure 9. *F(V)* vs. *V* plot of Cu/n-GaP/Al Schottky diode

where n is the n calculated from the lnI–V plot and γ is an integer greater than the n value. F(V) is the minimum point in the F(V)–V plot, V and I are the corresponding min. voltage and current, respectively. Also, the series resistance and BH values are determined follow as;

$$\Phi_B = Fm + \left[\frac{(\gamma - n)}{n}\right]\left[\frac{V_m}{\gamma} - \frac{kT}{e}\right] \tag{15}$$

$$\mathrm{R} = (\gamma - n)(\frac{kT}{eI_m}) \tag{16}$$

In 1967, Nicollian and Goetzberger reported that the frequency dependency of the series resistance can be determined with help the measurements of C–V–f and G/o–V–f curves [32]:

$$s = \frac{G_{max}}{(G_{max}^2 + (wC_{max})^2)} \tag{17}$$

where G_{max} and C_{max} are values of conductance and capacitance performed at 100kHz. Figure 10 (a) and (b) show conductance-voltage and series resistance-voltage plots of the Cu/n-GaP/Al Schottky diode. Curves is observed conductivity and capacitance at an increase about 2V owing to the interface states at 100kHz. Series resistance is going through a peak due to this increase, and this peak also shows a parallel behaviour to the peak in the C-V curves.

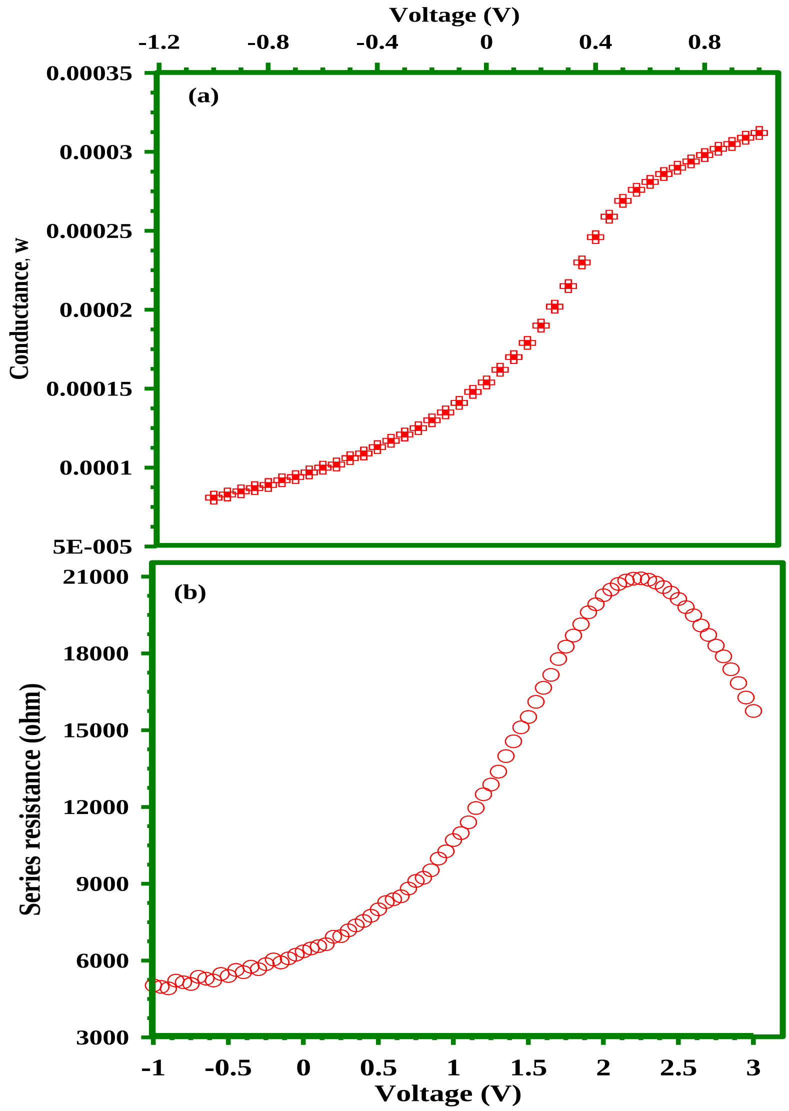

Figure 10 (a) and (b). G/w-V and Series resistance vs. Voltage plots of Cu/n-GaP/Al Schottky diode at 100kHz

4. Conclusions

We investigated the electrical properties on Cu/n-GaP/Al Schottky diodes. Its BH decreased when n of Cu/n-GaP/Al Schottky diode increased. Also, it is observed that the series resistance values which are calculated with three different methods increased for Cu/n-GaP/Al Schottky diodes. In addition, the parameters of Cu/n-GaP/Al Schottky diodes such as capacitance, built-in potential, donor concentration, Fermi level and BH obtained from $1/C^2$-V curves changed at room temperature. For this reason, there may be a mixture of different metallic phases with different BHs at diodes interfacial due to incomplete interfacial reaction. Thermionic field emission, Image force-lower, interfacial states, generation-recombination and are the mechanisms gave rise to the large values of the n. With the help of these calculated mechanisms can be obtained the absulate value of n.

Furthermore, the contamination at a interfacial is frequently exhibit at the interfacials of junction prepared by the routine processing methods used in the semiconductor electronics industries. These contaminants may act directly to introduce inhomogeneity or they may simply promote inhomogeneity, through the generation of defects, additional interfacial chemical phases and etc. BH inhomogeneity may be present even if the absence of chemical contaminants. Thus, interfacial roughness may contribute to the presence of BH inhomogeneity due to effectively increasing or decreasing the low-BH patches. Eventually, there are numerous, grain boundaries, stacking faults, dislocations, structural defects, at interfacials, and these may be the mean reason of BH inhomogeneity [33-34], [14].

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