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Araştırma Makalesi / Research Article

General electrical characterisation of $Ag/TiO_2/n\text{-}InP/Au$ Schottky Diode

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Abstract

In this study $Ag/TiO_2/n\text{-}InP/Au$ structures are formed on 500 µm thick, (100) oriented n-InP semiconductor having $3.13x10^{18}$ cm^{-3} carrier density, by using sputtering method. TiO_2 is grown as an interface with thickness of 60 Å. Some parameters of this structure are investigated in temperature range of 120- 360 K. It is noticed that there are two linear regions in forward bias current-voltage (I-V) plot. These two regions are called as LBR (low bias region) and MBR(middle bias region). Richardson coefficient is determined and mean barrier height is calculated with double Gaussian distribution.

Keywords: TiO_2, n-InP, Richardson coefficient, Gaussian distribution, Schottky.

$Ag/TiO_2/n\text{-}InP/Au$ Schottky diyodu için Gaussian dağılımı

Öz

Bu çalışmada, püskürtme metodu ile $Ag/TiO_2/n\text{-}InP/Au$ yapılar, 500 µm kalınlığında (100) yönelimli ve3.13x10^{18} cm^{-3} taşıyıcı yoğunluğuna sahip n-InP yarı iletkeni ile büyütülmüştür. TiO_2 , 60 A kalınlığında bir arayüz olarak büyütülmüştür. Bu yapının bazı parametreleri 120-360 K aralığında incelenmiştir. Akım-Voltaj (I-V) grafiğinde iki farklı lineer bölgenin olduğu farkedilmiştir. Bu iki bölge LBR (düşük beslem bölgesi) ve MBR (orta beslem bölgesi) olarak adlandırılmıştır. Richardson sabiti ve ortalama bariyer yüksekliği, çift Gaussian dağılımı ile hesaplanmıştır.

Anahtar Kelimeler: TiO_2, n-InP, Richardson sabiti, Gaussian dağılımı, Schottky.

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1. Introduction

Metal-semiconductor structures is a significant research area. Construction and characterisation of these devices are also important in terms of forming new and useful technological devices. Schottky contacts take great attention in scientific world because it is still not clear how Schottky barrier is formed. In order to analyses formation of this barrier numerous studies are being made by different researchers around world.

In this study n-InP is used as the substrate. InP is chosen because it is an interesting III-V group semiconductor and it has many applications in opto-electronic devices. InP has direct band gap and high electron mobility. Together with these advantages, InP also has some disadvantages. For example, low barrier height and great leakage current. This situation deteriorates performance of the device. Diodes with low barrier height are being widely used in thermal imaging systems, infrared detectors and sensors. It is possible to increase this low barrier height by using an interfacial layer. In this study TiO_2 interface with a thickness of 60 Å is used. The reason for choosing TiO_2 as an interface is, it diffuses to n-InP better with sputtering method. It also changes work function and effects parameters in a good way.What happens during growth of TiO_2 by sputtering method is as follows: In sputtering system cap of sputtering device is closed after the sample is inserted into sputtering unit for vacuming. Air in this unit is pomped out untill reaching the desired pressure value. Sputtering operation starts with charging the target metal (Ti) as positive. Atmosphere of sputtering unit is adjusted as O_2 gas. Charging Ti as positive causes an electric field in the unit and as a result a plasm medium occurs. Negatively charged O_2 ions hits Ti metal very fast and there occurs a momentum transfer. Ti particles leave the metal body with this transfer. These particles pass across the plasm region combining with O_2 and sticks to surface of sample. As a result sample is coated with TiO_2. (Güzelçimen et al., 2020., Çokduygulular et al. 2020)

2. Materials and Methods

In order to construct a good MS contact qualified and very well cleaned crystals should be used. In order to clean the crystal and remove organic and heavy metal dirts on the surface of n-InP, it is cleaned chemically in ultrasonic bath. After chemical cleaning procedure sample is dried in high purity N_2 atmosphere. Au ohmic contact is formed by sputtering method. During this procedure pressure of sputtering system is adjusted as $2x10^{-6}$ Torr. 150 nm thick almost pure (%99.995) Au is coated to rough side of substrate with sputtering method. During this coating period samples are kept at 80 ^oC temperature. Later in order to form ohmic contact sample is annealed at 325 ^oC for 4 minutes.

In O_2 medium Ti is sputtered on polished side and TiO_2 interfacial layer with a thickness of 60 Å is formed. To construct rectifying contact on polished side of substrate sputtering system is used again. Over the surface of this interfacial layer Ag is coated with a thickness of 1500 Å by using a steel mask. At the end of this operation Ag/TiO_2/n-InP/Au Schottky diode is produced.

3. Results & Discussion

I-V characteristics of Ag/TiO_2/n-InP/Au structure in forward bias is given in Figure 1. These characteristics are measured in temperature range of 120-360 K. In Figure 1 it is noticed that in each I-V curve there are two different linear regions. These regions are named as LBR and MBR for low bias and middle bias voltages, respectively. Also in each I-V curve there is a deviation from linearity caused from effect of series resistance (R_s) and interface layer. Because, applied voltage will be shared by interface layer (V_i), depletion layer (V_s) and R_s combination. LnI-V characteristics obviously show that there is a double exponential relation between current and applied voltage in low and middle bias. This behaviour implies that there are two different barrier heights parallel to each other in forward bias(Tecimer et al., 2012). For this reason current can be determined with equation (1).

$$I = I_{s1}\left\{\exp\left(\frac{q(V-IR_s)}{n_1 kT}\right)-1\ \right\} + I_{s2}\left\{\exp\left(\frac{q(V-IR_s)}{n_2 kT}\right)-1\ \right\}\frac{V-IR_s}{R_{sh}} \tag{1}$$

Here T is temperature in Kelvin, IR_s is the voltage on R_s, I_{s1} and I_{s2} are reverse saturation currents, n_1 and n_2 are ideality factors corresponding to LBR and MBR components. R_s in equation (1) is valid when n is larger than 1(V>3kT/q). Is values in LBR and MBR regions are determined with y-axis intercept points of linear parts of LnI-V plots at each temperature. Φ_{B0} values are calculated for each temperature with equation (2) by using I and S values(Rhoderick et al., 1988., Sze et al., 2007)

$$\phi_{B0} = \frac{kT}{q}\ln\left(\frac{SA^{*}T^{2}}{I_s}\right) \tag{2}$$

Here S is rectifier contact area of diode, Φ_{B0} is barrier height at zero bias, A* is Richardson coefficient, q is electronic charge and k is Boltzmann constant. Ideality factor (n) is described for deviations from Termionic Emission (TE) theory and calculated by using slope of linear regions in LnI-V plots for each temperature with equation (3) (Janardhamal et al., 2009).

$$n = \frac{q}{kT}\left(\frac{dV}{dLnI}\right) \tag{3}$$

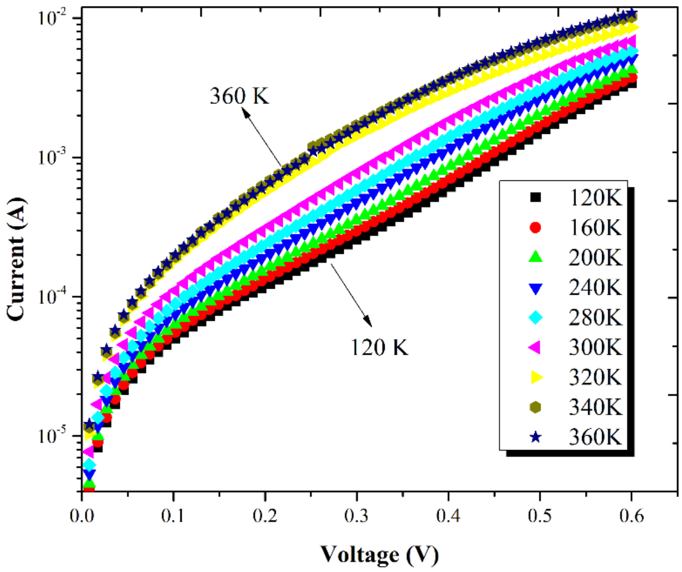

Figure 1. Forward bias I-V-T characteristics of Ag/TiO_2/n-InP/Au structure**.**

I_s, Φ_{B0} and n values gained from LBR and MBR voltage ranges are given in Table 1. It can be seen that they are strong functions of temperature. As can be seen in Table 1, (n.T) is almost constant for both LBR and MBR regions. This situation stems from parallel linear regions in LnI-V plots. Also this result may be a clue for tunnelling by means of interface states (Padovani et al., 1966).

In Figure 2 it can be seen that for both regions Φ_{B0} and n decrease unexpectedly with increasing temperature. It is obvious that these parameters are extremely large at low temperatures. That is, they change inversely proportional with temperature. This behaviour is a clue for deviation of n and Φ_{B0} from TE. Because according to TE Φ_{B0} is expected to decrease, for this reason temperature coefficient of Φ_{B0} (α=dΦ_{B0}/dT) should be similar to negative of temperature dependency of forbidden energy band gap of semiconductor. In addition to this value of n is expected to be near to 1. On the other hand, variation of Φ_{B0} with temperature shows an unexpected behaviour for both regions. Φ_{B0} value increase with increasing temperature instead of decreasing. It has positive temperature coefficient. In other words, positive temperature coefficient for Φ_{B0} is an opposition for ideal diodes. Furthermore, linear regions of LnI-V plots are parallel to each other in both voltage ranges at each temperature. So value of ideality factor decrease with increasing temperature. But (n.T) is almost constant. Similar results are gained by different researchers in literature (Saxena., 1969). As can be seen in Figure 3 ideality factor increase linearly with inverse of temperature, this is given with equation (4).

$$n(T) = n_0 + \frac{T_0}{T} \tag{4}$$

Here n_0 and T_0 are coefficients. Tunneling current parameter E_0 changes according to equations (5, 6, 7) dependent on temperature.

$$E_{00} = \frac{n_{tun} kT}{q} E_{00} \coth\left(\frac{qE_{00}}{kT}\right) \tag{5}$$

$$n_{tun} = \frac{E_{00}}{kT} \coth\left(\frac{E_{00}}{kT}\right) = \frac{E_{00}}{kT} \tag{6}$$

$$E_{00} = \frac{h}{4\prod}\left(\frac{N_D}{m_e * \varepsilon_s}\right)^{1/2} \tag{7}$$

Here n_{tun} is tunneling ideality factor, m_e* is mass of free electron, ε_s is dielectric coefficient of semiconductor and N_D is density of donor dopant atoms.

As can be seen in Figure 6, there is a linear relation between nkt/q-kT/q plots gained from theorical and experimental data and their slopes are almost constant. Slope of these plots give activation energy value. These results show that field emission theory (FE) is more dominant according to other current conduction mechanisms in Ag/TiO_2/n-InP/Au structure especially at low temperatures.

Table 1. Some parameters gained for Ag/TiO_2/n-InP/Au structure at different temperatures**.**

	LBR				MBR			
T (K)	I_{s1} (A)	n_1	n_1.T(K)	Φ_{B01}(eV)	I_{s2}(A)	n_2	n_2.T(K)	Φ_{B02}(eV)
120	5.58E-06	3.9	479.2	0.14	2.26E-05	11.4	1371.3	0.18
160	1.20E-02	3.0	488.7	0.16	5.60E-02	11.2	1798.0	0.14
200	1.20E-02	2.4	488.6	0.21	5.73E-02	9.2	1846.0	0.18
240	1.28E-02	2.1	526.3	0.26	5.95E-02	7.9	1909.2	0.23
280	1.28E-02	1.8	526.2	0.31	5.95E-02	6.8	1909.1	0.27
300	1.28E-02	1.7	526.1	0.34	6.31E-02	6.7	2020.1	0.29
320	1.26E-02	1.6	520.3	0.36	6.09E-02	6.1	1957.5	0.32
340	1.28E-02	1.5	526.1	0.39	6.45E-02	6.0	2069.0	0.34
360	1.36E-02	1.5	563.9	0.41	6.45E-02	5.7	2069.1	0.36

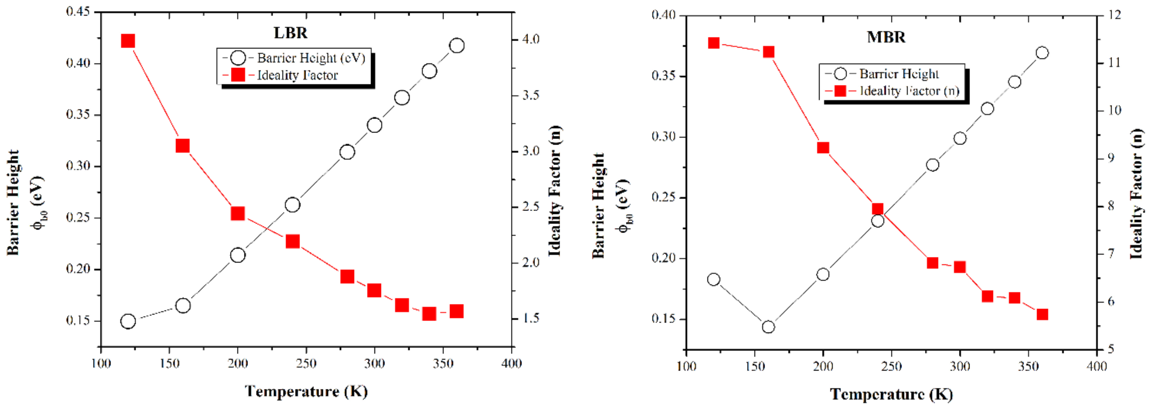

Figure 2. Φ_{B0}-T and n-T plots for Ag/TiO_2/n-InP/Au structure in LBR and MBR

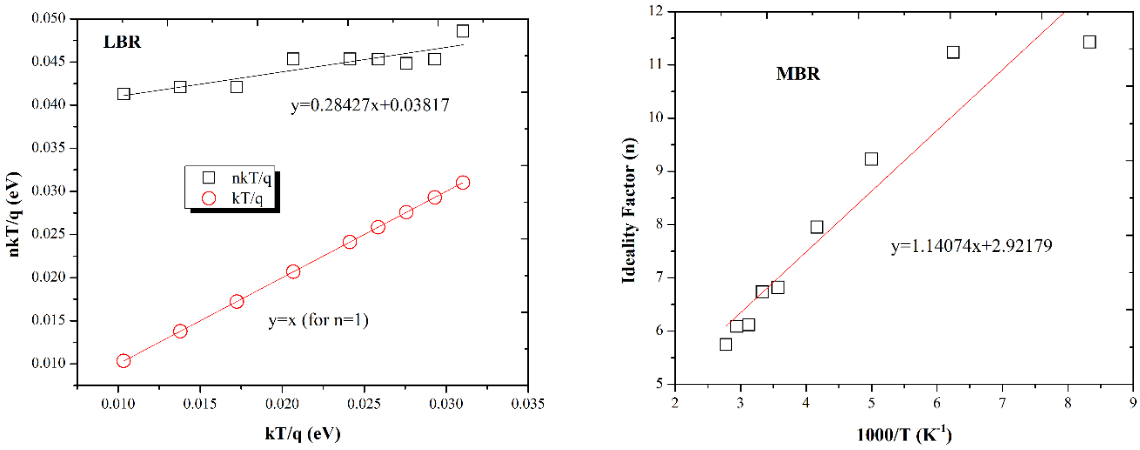

Figure 3. n-1000/T plots for Ag/TiO_2/n-InP/Au structure in LBR and MBR.

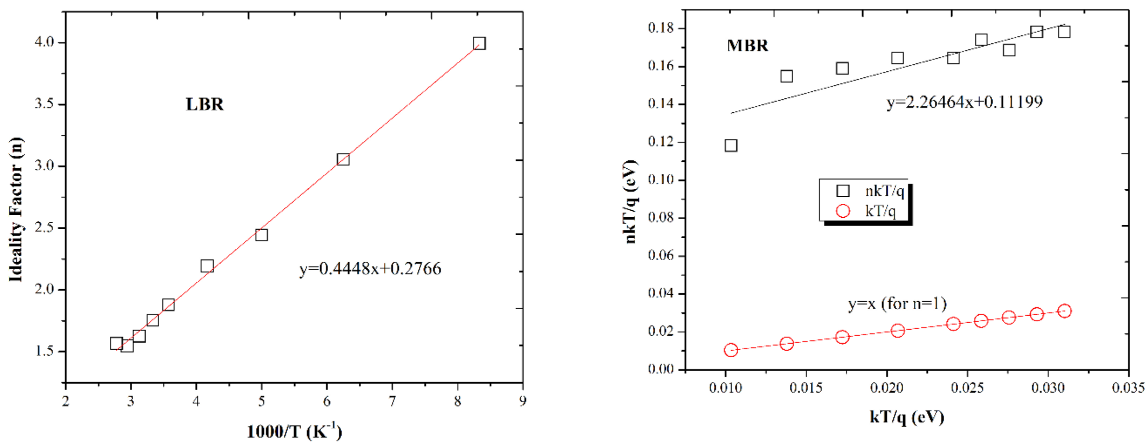

Figure 4. nkT/q-kT/q plots for Ag/TiO_2/n-InP/Au structure in LBR and MBR.

The significant increase in Φ_{B0} value and decrease in n with increasing temperature may stem from inhomogeneity of barrier at M/S interface. This variation in the values of Φ_{B0} and n, dependent on temperature, may be described with a mean barrier height at interface or many small barriers with a different name patches and their TE based Gaussian distribution. The reason for this inhomogeneity at interface may be attributed to polycrystal structure of metalic layer, different oriented crystolography, thermal operations, interface layer and inhomogeneity of it (Tecimer et al., 2013). This abnormal behaviour in barrier height, dependent on temperature, is explained by Song and co-workers with a private distribution of barrier height at interface (Song et al., 1986). Also, Schmitsdorf and co-workers found out that there is a linear relation between ΦB0 and n. As can be seen in Figure 5 Φ_{B0} versus n plot has two different linear regions for LBR and MBR. First of these regions is between 120-200 K and second is between 240-360 K temperature range and they are named as low temperature region (LTR) and high temperature region (HTR) respectively. Mean barrier height for ideal value of ideality factor (n=1) are found as 0.83 and 0.36 eV for first and second slopes in LBR and 0.80, 0.36 eV for MBR. In both plots the significant increase in Φ_{B0} and decrease in n with increasing temperature stems from inhomogeneity of barrier height at interface. In order to explain this abnormal deviation in pure TE, some researchers used TE based Gaussian distribution (Schmitsdorf et al., 1997). According to GD theory at M/S interface the relation between Φ_{B0} and T can be given with equation (8).

$$\phi_{B0} = \overline{\phi_{B0}}(T=0) - \frac{q\sigma_0^{\ 2}}{2kT} \tag{8}$$

Here, Φ_{B0} is zero bias barrier height or appearent barrier height and σ_s is standart deviation of barrier height at zero bias. σ_s value dependent on temperature is generally small and can be neglected. In addition to this, variation of ideality factor dependent on temperature according to GD theory can be given with equation (9) (Tung., 2001).

$$(\frac{1}{n} - 1) = \rho_2 - \frac{q\rho_3}{2kT} \tag{9}$$

In the light of descriptions above, both Φ_{B0} and (n^{-1}-1) versus q/2kT plots are drawn as a clue for GD theory in Figure 5.

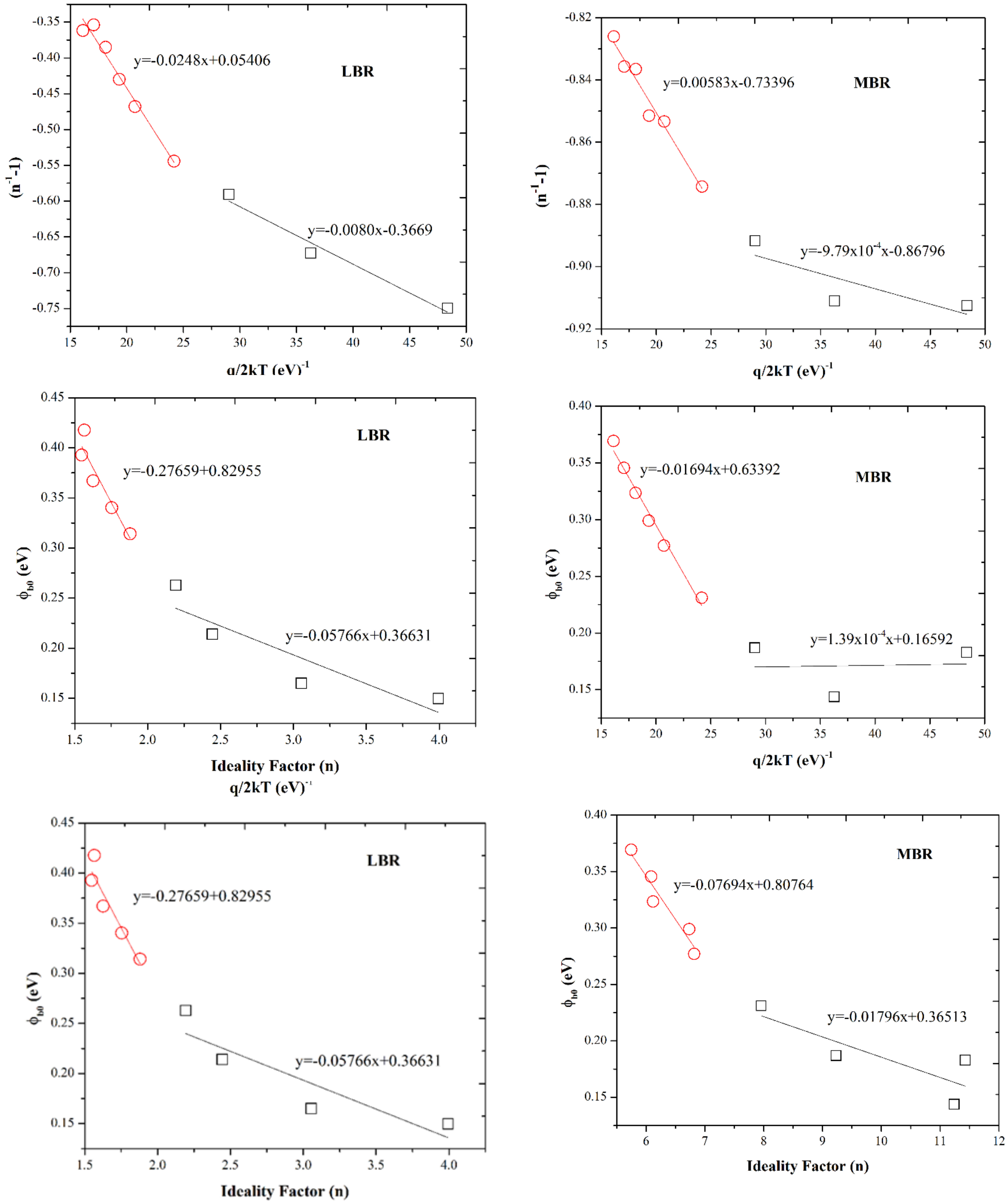

Figure 5. Φ_{B0}-n, Φ_{B0} and (n^{-1}-1) versus q/2kT plots for Ag/TiO_2/n-InP/Au structure in LBR and MBR.

As can be seen in Figure 5, Φ_{B0}-q/2kT plot has two different linear regions for LTR and HTR. For LBR and MBR regions, y axis intercept point and slope of these two regions give Φ_{B0} and σ_s.

They are found as 0.71 eV, 0.137 V and 0.63 eV, 0.13 V for HTR, 0.29 eV, 0.055 V and 0.16 eV, 0.51 V for LTR, respectively. Small value of σ_s implies inhomogeneity of barrier height.

$(n^{-1}-1)$ versus q/2kT plot in Figure 5 also has two different linear regions corresponding to LTR and HTR. Y- axis intercept and slope of these two linear regions give ρ_2 ans ρ_3 respectively. In LBR and MBR regions they are found as -0.0248, 0.054, 0.0058, 0.73 Volts and -0.008, -0.36, -9.8x10-4, 0.86 Volts for HTR and LTR respectively. This behaviour of $(n^{-1}-1)$ vs q/2kT plot implies there is a voltage deformation in barrier height. So, traditional Richardson plot can be modified by using σ_s values. This modification is shown in equation (10) (Hudait et al., 2001).

$$\ln\left(\frac{I_0}{T^2}\right)-\left(\frac{q^2\sigma_s^{\,2}}{2k^2T^2}\right)=\ln(AS)-\frac{q\overline{\phi_{B0}}}{kT} \tag{10}$$

$(Ln(I_0/T^2)-(q^2\sigma^2/k^2T^2))$ versus q/kT modified Richardson plots are shown in Figure 6 for both LBR and MBR.

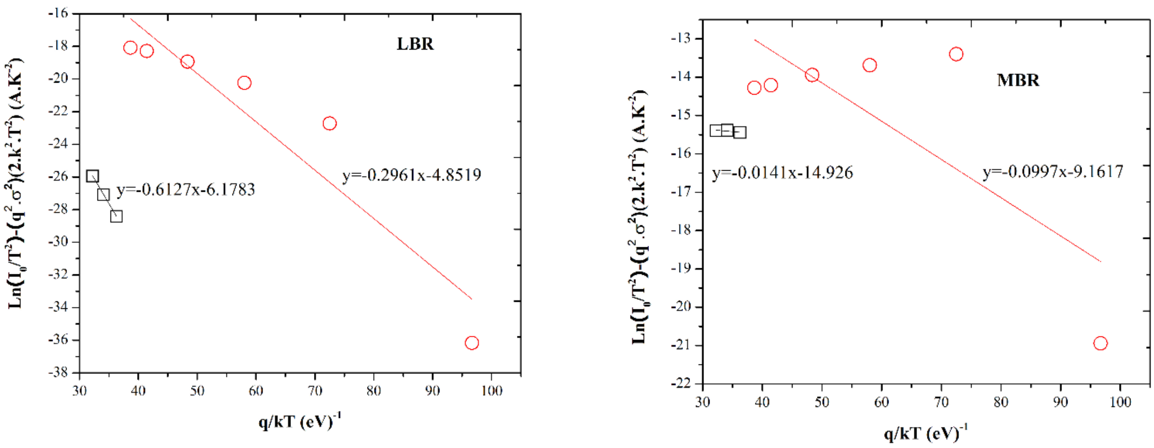

Figure 6. Modified Richardson plots for LBR and MBR**.**

As seen in Figure 6 modified Richardson plot for LBR and MBR has two different linear regions corresponding to LTR and HTR. Y-axis intercept and slope of these linear regions give Ln(A*S) and mean barrier height according to equation (10), respectively. Here S is the area of rectifying contact. In LBR, A* and Φ_{B0} values are gained as 0.26 $Acm^{-2}K^{-2}$, 0.61eV and 0.99 $Acm^{-2}K^{-2}$, 0.29 eV for HTR and LTR, respectively. In MBR, A* and Φ_{B0} values are gained as 4.1x10-5 $Acm^{-2}K^{-2}$, 0.014 eV and 0.013 $Acm^{-2}K^{-2}$, 0.09 eV for HTR and LTR, respectively.

In the light of these results, it is noticed that deviation from TE theory stems from spacial distribution of barrier height at interface and carriers passing through metal from semiconductor shows energy low at low temperature (Chand et al., 1997). This situation results with a significant increase in ideality factor. At high temperatures, electrons gain more energy and they can pass the barrier directly. That is, at high temperatures there is no need to use patches for electrons and they do not contribute to the current. As a result of this ideality factor decrease. In summary, high ideality factor gained at low temperatures can not be explained either with FE or TFE.

I-V-T characterisation results show that there is a significant deviation from ideal situation and TE. In other words, I-V-T results are not obeying TE theory. Because, I-V-T characteristics according to TE theory show that Φ_{B0} value increase linearly and ideality factor decrease exponentially with increasing temperature. Increase in Φ_{B0} value with increasing temperature is against negative temperature coefficient of forbidden energy band gap of the semiconductor. Furthermore, variation of Φ_{B0} and n at low temperatures results with deviation from linearity in classical Richardson plot. These deviations may have many reasons. The most important reasons are, preparation procedure of the sample, shape of barrier at MS interface and nature of interface layer, interface states, impurities in semiconductor and dislocations, density of dopant atoms, sample temperature, series resistance and applied voltage (Özdemir et al., 2006). High values of ideality factor are explained with existance of interface states (Janardhamal et al., 2009), barrier drop because of high electric field (Rhoderick et al., 1988), recombination of charges (Sze et al., 2009., Janarhamal et al., 2007) in literature. In this study, large values of n even at high temperatures can not be explained only with these reasons. Because the equation (11) for ideality factor in literaure is as (Rhoderick et al., 1988., Janardhamal et al., 2009),

$$n = 1 + \frac{d_i}{\varepsilon_i}\left[\frac{\varepsilon_s}{W_d} + qN_{ss}\right] \tag{11}$$

Here, d_i, ε_s, ε_i, W_d and N_{ss} are, thickness of insulator layer, dielectric coefficient of semiconductor, dielectric coefficient of interface, thickness of depletion region and density of interface states respectively. Ideality factor values gained for LBR and MBR can not be explained with equation (11) even at high temperatures. They can be explained with inhomogeneity of barrier (Shenoy et al., 2005). In other words inhomogeneity of barrier results with high ideality factor. Especially at low temperatures, because of obsenit current conduction mechanisms, Φ_{Bo} and n values gained from TE are not so trustable. Because contribution of other obsenit current conduction mechanisms to measured current, increase with decreasing temperature (Tung., 2001). Similar results are gained by many researchers in recent years (Janardhanam et al., 2013).

4. Conclusion

As a result of this study, current conduction mechanism for Ag/TiO_2/n-InP/Au structure can be explained with double Gaussian distribution succesfully. It is also seen that TFE and FE mechanisms are effective especially at low temperatures. In the light of experimental results gained, it can be said that investigation of I-V-T characteristics at low temperatures is extremely important. Because at temperatures above room temperature, TE theory is more dominant because of extra energy of carriers and decreasing barrier height. For this reason, in order to gain true and trustable knowledge on shape of barrier at interface and current conduction mechanisms, investigation of I-V-T characterictics at low temperatures is more suitable. Also, In LBR, A* and Φ_{B0} values are gained as 0.26 $Acm^{-2}K^{-2}$, 0.61eV and 0.99 $Acm^{-2}K^{-2}$, 0.29 eV for HTR and LTR, respectively. In MBR, A* and Φ_{B0} values are gained as 4.1x10-5 $Acm^{-2}K^{-2}$, 0.014 eV and 0.013 $Acm^{-2}K^{-2}$, 0.09 eV for HTR and LTR, respectively.

Deviation voltages from standart barrier height are found as in LBR and MBR regions -0.0248, 0.054, 0.0058, 0.73 Volts and -0.008, -0.36, -9.8x10-4, 0.86 Volts for HTR and LTR respectively

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Authors' Contributions

All authors contributed equally to the study.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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