The analysis of Au/$Ti0_2$/n-Si Schottky barrier diode at high temperatures using I-V characteristics

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In this study, the current-voltage (*I-V*) characteristics of Au/TiO_2/n-Si Schottky barrier diodes (SBDs) were examined at high temperatures. TiO_2 thin films were deposited on polycrystalline n-type Silicon (Si) substrate using DC magnetron sputtering system. In order to improve the crystal quality, thermal anneling process were done at 700 ^{0}C. The electrical parameters such as barrier height (Φ_b), ideality factor (*n*) and series resistance (R_s) of Au/TiO_2/n-Si SBDs have been investigated by using forward and reverse bias *I-V* measurements in the temperature range of 340-400 K by steps of 20 K. Also, the values of R_s and Φ_b were determined by using Cheung's and Norde methods. It was seen that there was a good agreement between the values of R_s and Φ_b obtained from the forward bias *ln*(*I-V)* curves by applying Cheung's and Norde methods.

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1. Introductıon

TiO_2 is a wide band gap semiconductor material which has attracted considerable attention for its potential applications in optical components such as photocatalysis, gas sensor, solar cell and optical fiber [1-4]. It has three types of bulk crystal structure in TiO_2: anatase, rutile and brookite [5]. Among these crystal, anatase TiO_2 has attracted a greed deal of interest because of its excellent photocatalytic behaviour. It is known that the deposition method and calcination temperatures determine the physical properties of the TiO_2 material. Depending on the calcination temperature TiO_2 films transform first from amorphous to anatase and then rutil. [6]. Although a variety of methods have been used to prepare TiO_2 films, sputtering is one of the most utilized method. [7].

Recently, there were published many studies on SBDs which has an important role in modern device technology [8-16]. The electrical properties of the SBDs depend especially on the series resistance of device. There are various techniques to calculate the main electrical parameters such as forward bias *I-V* measurements, Cheung's method [17] and Norde method [18]. Electronic properties of a Schottky diode are characterized by its main electrical parameters such as *n*, Φ_b and R_s which are parameters give useful information concerned with the nature of the diode. Analysis of the *I-V* characteristics of SBDs based on thermionic emission theory usually reveals an abnormal decrease in the BH and an increase in the ideality factor with a decrease in temperature [19, 20].

In this study, *I-V* characteristics of Au/TiO_2/n-Si SBDs with anatase phase TiO_2 were measured in the temperature range of 340-400 K by steps of 20 K. The temperature dependence of electrical parameters such as n, Φ_b and R_s were extracted from forward bias *I-V* measurement. Also, Φ_b and R_s were calculated using Cheung's and Norde methods. It was seen that there was a good agreement between the values of R_s and Φ_b obtained from the forward bias *lnI-V* curves by applying Cheung's and Norde methods.

2. Experimental procedure

Au/TiO_2/n-Si SBDs were fabricated on a 2" diameter with (100) orientation, 350 μm thickness, 0.01 Ω.cm resistivity and phosphorus doped (n-type) polycrystalline Si substrate. Si substrate was

degreased using organic solvent. After then, the Si substrate was mounted onto the stainless steel optically heated sputtering holder and loaded into the DC magnetron sputtering system. After the preparation of the substrate to the deposition of 1500 Å thickness TiO_2 thin film, the Si substrate was transferred into the deposition chamber. TiO_2 thin film was deposited using high purity (99.999%) Ti target, under specific Ar+O_2 reactive gas mixture (Ar/O_2=90/10 sccm) controlled with mass flow controllers. For the deposition, the substrate temperature and the pressure was set to 200 ^{o}C and 4.2×10^{-3} mbar, respectively and kept constant during the whole deposition. The thermal annealing of the sample was carried out in air for 4 h at 700 ^{o}C. For the electrical characterization, in the thermal evaporation system ohmic and rectifier contacts were formed using high purity Au (99.999%).

The forward and reverse bias *I-V* measurements were performed in the temperature range of 340 - 400 K using a Keithley 2400 source-meter. The temperature was adjusted using Janis vpf-475 cryostat and a Lake Shore model 321 auto-tuning temperature controllers with sensitivity better than ± 0.1 K. The whole electrical measurements were also performed using micro computer through an IEEE-488 AC/DC converter card.

3. Results and discussion

The current-voltage (*I-V)* characteristics of Au/TiO_2/n-Si SBDs in the temperature range of 340-400 K by steps of 20 K are given in Fig. 1. In order to quantitatively analyze the Au/TiO_2/n-Si SBDs we assume the standard thermionic emission (TE) theory as follows [21]

$$I = I_o \exp\left(\frac{q(V - IRs)}{nkT}\right) \quad (1)$$

Where the IR_s term is the voltage drop across the R_s of structure, V is the applied voltage across to rectifier contact, I_o saturation current is defined by

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

The quantities *A*, *A**, *T*, *k* and *q* are the diode area, the effective Richardson constant of 112 A/cm^{2}K^2 for n-type Si, temperature in Kelvin, Boltzmann constant and electronic charge, respectively.

Once I_o is determined the Φ_b is obtained by rewriting Eq. (2) as

$$\Phi_b = \frac{kT}{q} \ln\left[\frac{AA^* T^2}{I_0}\right] \quad (3)$$

The *n* can be calculated from the slope of the linear region of the forward bias *ln*(*I-V)* plot for each temperature and can be written from Eq.(1), as

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

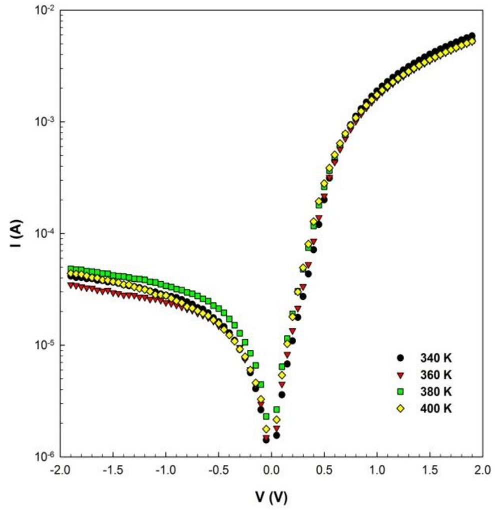

Fig. 1. Temperature dependent semi-logarithmic plot of the lnI-V characteristics of Au/ TiO_2/n-Si SBDs with anatase phase TiO_2 at various temperatures.

Table 1. Temperature dependent of various parameters determined from I-V characteristics of Au/TiO_2/n-Si SBDs.

T (K)	Φ_b(I-V) (eV)	R_s(dV/dln(I)) (Ω)	Φ_b(H(I)) (eV)	R_s(H(I)) (Ω)	Φ_b(F(V)) (eV)	R_s(F(V)) (Ω)
340	0.74	179.85	0.78	199.07	0.78	156.4
360	0.78	172.65	0.86	211.08	0.82	170.92
380	0.82	178.81	0.88	231.24	0.84	212.59
400	0.85	184.33	0.93	217.03	0.88	217.89

Using Eqs. (3) and (4) the values of Φ_b and *n* of the Au/TiO_2/n-Si SBDs at different temperatures were calculated. The experimental values of Φ_b and *n* of Au/TiO_2/n-Si SBDs were changed from 0.74 eV and 2.47 at 340 K to 0.85 eV and 2.24 at 400 K, respectively. Also, R_s values were determined from the *I-V* characteristics. R_s values of Au/TiO_2/n-Si SBDs were changed from and 288.24 Ω to 318.56 Ω at 340 K and 400 K, respectively. The Φ_b calculated from forward bias *I-V* characteristics shows an unusual behavior that increase with the increase of temperature. Similar results have been reported in the literature [15]. Such temperature dependence was an obvious disagreement with the reported negative temperature coefficient of the Schottky barrier height.

Series resistance (R_s) and barrier height (Φ_b) were calculated from the forward bias *I-V* data using methods developed by Cheung and Cheung [17]. Cheung's function

$$\frac{dV}{dLnI} = n\frac{kT}{q} + R_s I \quad (5)$$

$$H(I) = V - n\frac{kT}{q}Ln\left(\frac{I_o}{AA^*T^2}\right) = n\Phi_b + R_s I \quad (6)$$

The experimental *dV/dln(I)* versus *I* and *H(I)* versus *I* plots of at different temperatures are given in Fig. 3 (a) and (b), respectively.

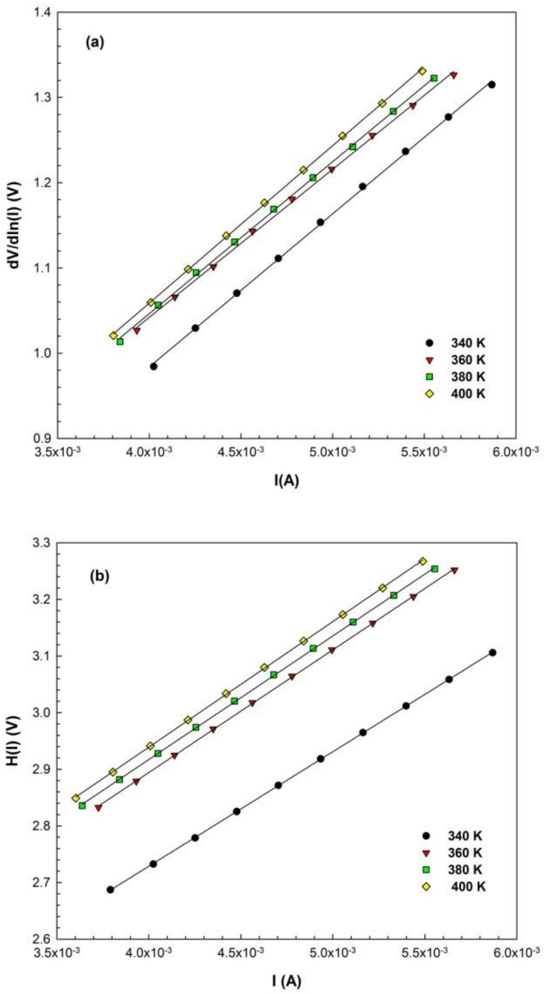

Fig. 2. (a) Experimental dV/dln(I) vs I and (b) H(I) vs I plots of Au/ TiO_2/n-Si SBDs at various temperatures.

The values of series resistance of Au/TiO_2/n-Si SBDs were calculated from both *dV/dlnI* versus *I* plot according to Eq. (5) and *H(I)* versus *I* plot according to Eq. (6) in the temperature range of 340 K to 400 K. The determined values of R_s and Φ_b are given in Table 1. As can be seen, the determined values of R_s (*dV/dln(I)* versus *I)* of Au/TiO_2/n-Si SBDs were changed from 179.85 Ω to 184.33 Ω at 340 K and 400 K, respectively. The determined values of R_s and Φ_b (*H(I)* versus *I)* of Au/TiO_2/n-Si SBDs were changed from 199,07 Ω and 0,78 eV at 340 K to 217,03 Ω and 0,93 eV at 400 K, respectively. It was seen in Table 1,The values of R_s obtained from *dV/dln(I)* versus *I* and *H(I)* versus *I* plots are in good agreement with each other. Also, the difference in the values of Φ_b obtained from Eqs (3) and (6) is an effect of existence of R_s and thickness interfacial layer

Norde proposed an alternative method to determine the value of the R_s and Φ_b. The values of R_s and Φ_b were obtained from the modified Norde method developed by Bohlin [22]. The modified Norde method is expressed as

$$F(V,\gamma) = \frac{V}{\gamma} - \frac{q}{kT}\ln\left(\frac{I}{AA^*T^2}\right) \quad (7)$$

where I is current obtained from the *I-V* curve, γ is the dimensionless value greater than ideality factor. A plot of F(V) versus V for Au/TiO_2/n-Si SBDs at different temperatures are given in Fig. 3 From the plot of F(V) versus V, the value of Φ_b can be determined as follows

$$\Phi_b = F(V_0) + \frac{V_0}{\gamma} \quad (8)$$

where F(Vo) is the minimum point of F(V, γ) versus V and Vo is the corresponding bias voltage. R_s can be experessed as

$$R_s = \left(\frac{kT}{qI}\right)(\gamma - n) \quad (9)$$

From the F(V) versus V plots the values of R_s and Φ_b were changed from 165,4 Ω and 0,78 eV at 340 K to 217,89 Ω and 0,88 eV at 400 K, respectively, by using the values $F(V_0)$ and V_0 were changed from 0,687 V and 0,599 V at 340 K to 0,798 V and 0,549 V, respectively. The R_s and Φ_b values from the modified Norde and Cheung's methods have been compared with each other and results were given in Table 1.

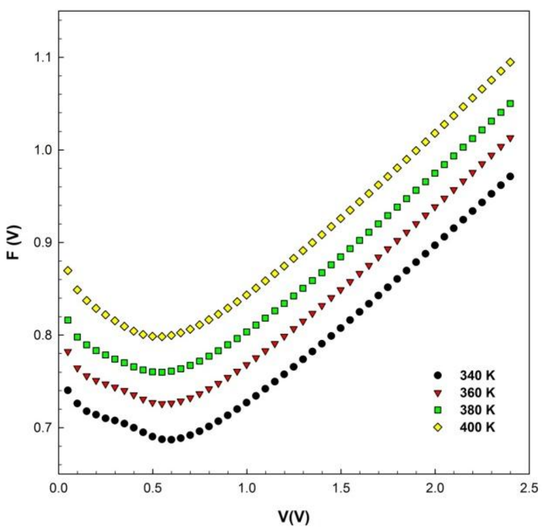

Fig. 3. F(V) vs V plot of the Au/ TiO_2/n-Si SBDs at various temperatures.

4. Conclusion

The forward and reverse bias *I-V* characteristics of Au/TiO_2/n-Si SBDs have been investigated in the temperature range of 340-400 K by steps of 20 K. The temperature dependence of electrical parameters were extracted from forward bias *I-V* measurement. Experimental results show that Φ_b and R_s values are found to be changing depending on temperature. The values of Φ_b and R_s have been obtained from two methods: Cheung's and Norde methods. It were found that Φ_b and R_s values obtained from the forward bias ln(I-V) curves by applying Cheung's and Norde methods were in good agreement with each other. In summary, in the present study, TiO_2 thin films were deposited on polycrystalline n-type Silicon (Si) substrate using DC magnetron sputtering system. In order to improve the crystal quality, thermal anneling process were done at 700 ^{0}C. After then, For the electrical characterization, in the thermal evaporation system ohmic and rectifier contacts were formed using high purity Au. Furthermore, Φ_b and R_s have been obtained from two methods and compare with each other.

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Reference

[1] L. Yang, S. S. Saavedra, N. R. Amstrong, J. Hayes, Anal Chem. **66**, 1254 (1994).
[2] K. Zawreska, M. Radeska, M. Rekas, Thin Solid Films **310**, 161 (1997).
[3] S. Ito, S. Kimatura, S. Yanagia, Solar Energy Mater Solar Cell **76**, 3 (2003).
[4] H. Kostlin, G. Frank, G. Hebbinghaus, H. Auding, K. Denisen, Journal of Non-Crystalline Solids **218**, 347 (1997).
[5] W. Yang, J. Marino, A. Monson, C.A. Woden, Semiconductor Science and Technology **21**, 1573 (2006).
[6] N. R. Mathews, E. R. Morales, M. A. Cortes-Jacome, J. A. Tolede-Antonio, Solar Energy **83**, 1499 (2009).
[7] L. Miao, P. Jin, K. Kaneko, A. Terai, N. Nabatova-Gabain, S. Tanemura, Applied Surface Science, **212-213**, 255 (2003).
[8] M. K. Hudait, P. Venkateswarlu, S. B. Krupanidhi, Solid State Electron **45**, 133 (2001).
[9] S. Chand, S. Bala, Semicond. Sci. Technol **19**, 82 (2004).
[10] J. Osvald, Solid-State Electron **50**, 228 (2006).
]11] K. Ejderha, N. Yıldırım, B. Abay, A. Turut, J. Alloys Comp **484,** 870 (2009).
[12] V. Janardhamam, A. A. Kumar, V. R. Reddy, P. N. Reddy, J. Alloys Comp **485,** 467 (2009).
[13] A. Tataroğlu, Ş. Altındal, J. Alloys Comp. **484**, 405 (2009).
[14] P. Durmuş, Ş. Altındal, A. Tataroğlu, J. Optoelectron. Adv. Mater. **12**(7), 1472 (2010).
[15] T. Tunç, İ. Dökme, Ş. Altındal, İ. Uslu, Optoelectron. Adv. Mater. – Rapid Commun. **4**(7), 947 (2010).
[16] M. Soylu, F. Yakuphanoğlu, W. A. Farooq, Optoelectron Adv. Mater. – Rapid Commun. **5**(2),135 (2011).
[17] S. K. Cheung, N. W. Cheung, Appl. Phys. Lett. **49,** 85 (1986).
[18] H. Norde, J. Appl. Phys. **50,** 5052 (1979).
[19] R. T. Tung, Mat. Sci. Eng. R **35,** 1 (2001).
[20] A. Gümüş, A. Türüt, N. Yalçın, J. Appl. Phys. **91**, 245 (2002).
[21] E. H. Rhoderick, R. H. Williams, Metal-Semiconductor Contacs, second ed., Clarendon Press, Oxford. (1988).
[22] K. E. Bohlin, J. Appl. Phys. **60**, 1223 (1986).

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