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Araştırma Makalesi / Research Article

Electrical Properties of The Heterojunction Diode Produced Based on IGZO Thin Film

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Keywords
IGZO; Thin film; Diode; Cheung-Cheung; Norde; PLD

Abstract

In this study, IGZO thin films were produced on SLG and p-Si wafer at low temperature, under oxygen gas pressure of 5×10^{-2} and 7×10^{-2} mbar, using PLD technique and these thin films were annealed at 300^{o}C temperature. IGZO thin films were grown in amorphous structure. As the oxygen gas pressure was increased, the particle size in the thin films were increased. IGZO/p-Si heterojunction diode was produced based on IGZO thin film that was deposited under oxygen pressure in 7×10^{-2} mbar and not annealed, and $J-V$ curves of this diode in darkness and under the illumination condition were obtained and then its barrier height and idelaity factor were calculated. In an illumination condition, n, R_s and Φ_b values of IGZO/Si heterojunction diode were calculated by the traditional $J-V$, Norde and Cheung Cheung methods. Results obtained in this work have been interpreted as well as concluded to be close to each other.

IGZO İnce Filme Dayalı Olarak Üretilen Heteroeklem Diyotun Elektriksel Özellikleri

Anahtar Kelimeler
IGZO; İnce film; Diyot; Cheung-Cheung; Norde; PLD

Öz

Bu çalışmada, PLD tekniği kullanarak oda sıcaklığındaki SLG ve p-Si wafer üzerine 5×10^{-2} ve 7×10^{-2} mbar oksijen gaz basıncı altında IGZO ince filmler üretilmiş ve 300^{o} C sıcaklıkta tavlanmışlardır. IGZO ince filmler amorf yapıda büyümüşlerdir. Oksijen gaz basıncı artarken, ince filmi oluşturan parçacıkların boyutu büyümüştür. 7×10^{-2} mbar oksijen gaz basıncı altında büyütülmüş ve tavlanmamış IGZO ince filme dayalı olarak IGZO/Si heteroeklem diyotu üretilmiş ve bu diyotun karanlık ve aydınlık şartlarda $J-V$ eğrileri elde edilmiş, ideality faktörleri ve bariyer yükseklikleri hesaplanmıştır. Aydınlık ortam için, $J-V$, Cheung Cheung ve Norde metotları ile IGZO/Si heteroeklem diyotun n, R_s and Φ_b değerleri hesaplanmıştır. Bu çalışmadan elde edilen sonuçlar analiz edilmiş ve bulunan değerlerin birbirlerine yakın olduğu yorumu yapılmıştır.

1. Introduction

Transparent Conductive Oxides (TCO) are typically materials having high optical transparency (80-90%) in the visible region, the wide band gap (because of the high electronegativity of oxygen in n-type TCOs, typically Eg ≥ 3.1 eV) and high electrical conductivity (Ikhmayies 2017). In the last two decades, interest in multicomponent TCOs such as Zinc Tin Oxide, Indium Tin Oxide (Sofi *et al*. 2018), Indium Zinc Oxide (Craciun *et al*. 2014, Zhang *et al*. 2019) has been dramatically increased (Altınkök and Olutaş

2020). Among these TCOs, a-IGZO (amorphous-Indium Gallium Zinc Oxide) has emerged as a encouraging candidate, with the high mobility of this material (Sheng *et al*. 2019). a-IGZO material with such high mobility is used to be channel layer in thin film transistors (TFT) (Suresh *et al*. 2007). a-IGZO can be produced in low temperature and exhibits a good mobility comparable to crystalline phase materials (Su *et al*. 2013, Erken 2020). The high mobility of a-IGZO consists of the ns-orbitals of the metal cation larger than 2*p*-orbital of the oxygen anion (Chang and Ju 2012). Also, a-IGZO is n-type semiconductor has distinct advantages over other semiconductors such as its usability in room temperature processes, good stability, high transparency in the visible region (380-750 nm), large energy band gap of 3.5 eV (Li *et al*. 2019), the low cost and environmental friendly composition (Moreira *et al*. 2019). IGZO thin film transistors detect UV light and are generally used in the application of UV detectors (Li *et al*. 2015). Thin-film transistors (TFTs) manufactured by polycrystalline Silicon (Si) and amorphous Si, which are the basic materials of existing flat panel displays and over glass systems. Nevertheless, Si-based TFTs are not suitable for high resolution images on inexpensive flexible substrates due to their high processing temperatures and low mobilities (<1 $cm^2/V.s$). Fortunately, oxide-based TFTs have high mobility and can be produced at low substrate temperatures. Due to the commonness of Si semiconductor manufacturing processes, it is very significant to examine the IGZO/p-Si hetero junction diode structures, where IGZO semiconductor can be a viable nominee to channel layer in a Si-based electronic device (Li *et al*. 2015, Xie *et al*. 2012). Band alignment between a-IGZO and Si semiconductors helps to foresee the electronic structures such as electron transport at the interface, band bending, built potential and performances of hetero junction devices (Chen *et al*. 2015).

Coating techniques such as Sputtering (Wang *et al*. 2015), Atomic Layer Deposition (ALD) (Cho *et al*. 2018) and Pulse Laser Deposition (PLD) (Chen *et al*. 2010, Mistry and Joshi 2016) are used for production of a-IGZO thin films. The homogeneous and smooth thin films can be produced, stoichiometric transfer can be succeeded by courtesy of adjustable parameters such as substrate temperature, laser fluency, background gas (oxygen) pressure with PLD technique (Gezgin and Kılıç 2019a, Gezgin and Kiliç 2019b). In this study, a-IGZO thin films were produced on p-Si wafer depending on the oxygen gas pressure using PLD technique. Ag/IGZO/p-Si/Al heterojunction diode structures were formed by a-IGZO thin films deposited on the Si wafer at room temperature and then annealed. $J-V$ curves of the heterojunctions were obtained in the dark and the illumination environment. The electrical parameters of the diodes were acquired using traditional $J-V$ method, Norde method and Cheung-Cheung method and interpreted comparatively for illumination conditions.

2. Material and Method

In this study, IGZO thin films were deposited on microscopic slide glass and p-type Si wafer at room temperature using an Nd: YAG laser (10 Hz repetition rate, 10 ns pulse width, 1064 nm wavelength). p-type Si wafer was used in 500 µm in thickness, in (100) orientation, in 8-12 Ω.cm resistivity and in 1 cm^2 area.

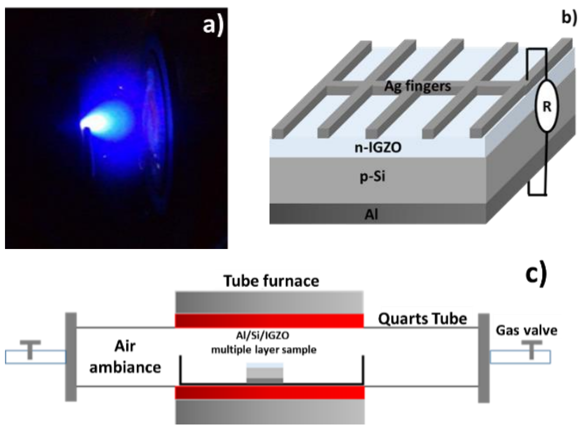


Figure 1. a) Plasma photo of IGZO particles ablated in $7x10^{-2}$ mbar oxygen gas pressure **b)** schematic images of Ag/IGZO/p-Si/Al hetero-junction diode and **c)** quartz tube furnace

The back surface of p-Si wafer has been coated by aluminium (Al) thin film using Physical Vapour Deposition (PVD). Then, in PLD system, the distance between substrate-target was set to 50 mm. The background pressure in vacuum chamber prior to experimenting was evacuated down to ~ $1x10^{-6}$ mbar. IGZO sputtering target (%99.99 pure) has been ablated by a laser beam at 40 mj energy. The plasma photograph of the ablated IGZO material is shown in Figure (Fig) 1a. IGZO thin films were grown on the front face of p-Si wafer and on microscopic glass at room temperature for 30 minutes under oxygen gas pressures about from $5x10^{-2}$ to 7×10^{-2} mbar. Oxide thin films were annealed at 300^{o}C temperature for 5 minutes in a quarts tube furnace (in Fig 1c). Ag thin film contacts were deposited on IGZO thin film by PVD technique. The schematic image of produced Ag/IGZO/p-Si/Al hetero-junction diode is given in Fig 1b.

X-Ray Diffraction (XRD), UV-vis spectrometer and Atomic Force Microscopy (AFM), were used to examine and analyse the crystal and optical properties, morphological structures of IGZO thin films produced, respectively. $J-V$ curves of IGZO/Si hetero-junction diode structures in darkness and under the illumination conditions were obtained and their electrical properties were discussed in some details.

3. Discussion and Results

3.1. Morphologic Analyse

AFM images of IGZO thin films grown under oxygen gas pressure of 5×10^{-2} mbar and 7×10^{-2} mbar, respectively, are given in Fig 2a and 2b.

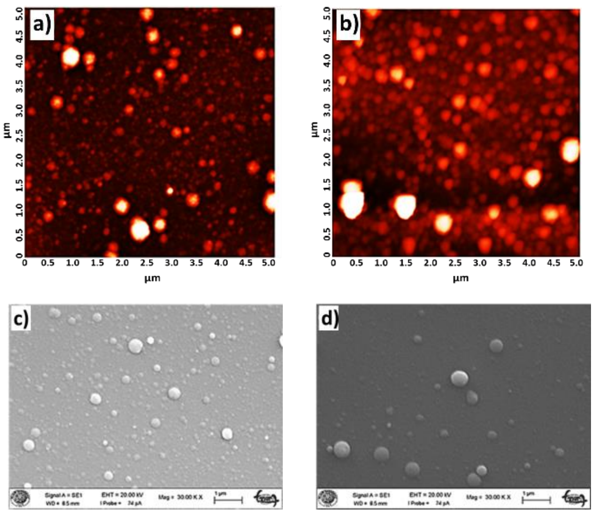


Figure 2. AFM and SEM images (in 5 µm × 5 µm area) of IGZO thin films grown in oxygen gas pressures of **a) and c)** 5×10^{-2} mbar, **b) and d)** 7×10^{-2} mbar, respectively

When the oxygen gas pressure increased to from 5x to 7×10^{-2} mbar, it was noticed and measured that the size of the particles forming IGZO thin film were increased (in Fig 2b and 2d) (Suda *et al*. 2002, Coetsee 2010). With an increase in oxygen gas pressure, the plasma formed by particles ablated from IGZO is compressed by the oxygen atoms. Thus, IGZO particles in the shrinking plasma collide with each other. Colliding particles in a plasma plume produced by laser beam from IGZO target combine with each other causing production of particles in larger size. The thicknesses of IGZO thin films grown in gas pressure of 5×10^{-2} mbar and 7×10^{-2} mbar were measured as 500 nm and 420 nm, respectively. The ablated IGZO particles trapped in the plasma were scattered to the environment and backward with the increasing oxygen gas pressure (Gezgin *et al*. 2020). Thus, thin film thickness decreases as the deposition rate and particle density decrease as seen in Fig 2d.

3.2. XRD Analyse

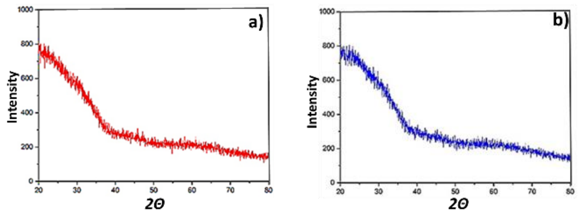
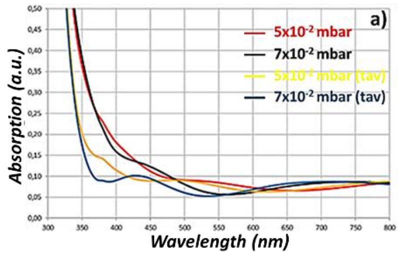


Figure 3. a) XRD Spectra of IGZO thin films grown in oxygen gas pressures of **a)** 5×10^{-2} mbar, **b)** 7×10^{-2} mbar

According to XRD spectra given in Fig 3, IGZO thin films deposited in oxygen gas pressures of 5×10^{-2} mbar and 7×10^{-2} mbar has grown in amorphous form. This situation is consistent with the results reported in literature (Lee and Dho 2011).

3.3. Optical Properties



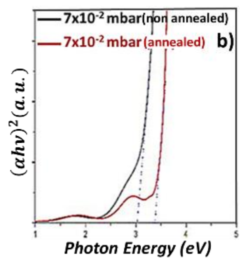


Figure 4. a) Absorption spectra of IGZO thin films produced on microscopic glass at room temperature in 5×10^{-2} mbar, 7×10^{-2} mbar oxygen gas pressure and annealed at 300°C temperature and **b)** Tauc graph of IGZO thin film produced at room temperature in oxygen gas pressure of 7×10^{-2} mbar and annealed at 300°C temperature

The absorption spectrum in Fig 4a shows that IGZO thin films (in 5×10^{-2} mbar, 7×10^{-2} mbar oxygen gas pressure and annealed at 300°C temperature) are highly transparent to light. In addition, these IGZO thin films show similar optical properties to each other in terms of absorption. Especially, the produced in 7×10^{-2} mbar oxygen gas pressures and annealed IGZO thin films, which tend to absorb light in UV and NIR region while transmitting light in visible region. This transparent oxide thin film exhibits an ideal optical property for use as n-type semiconductor (window layer) in solar cells (Lee *et al*. 2012, Azri *et al*. 2016).

Optical energy band gaps of IGZO thin films calculated using Tauc equation expressed below:

$$(\alpha h v)^2 = A\left(hv - E_g\right)^{1/2} \quad (1)$$

The photon energy is expressed as hv, energy band gap of thin films is E_g and the constant value in Eq. 1 is shown as A. E_g is plotted by calculating $(\alpha hv)^2$ against (hv) in Tauc plot (Gezgin *et al*. 2019), indicated in Fig 4b. The deposited in oxygen gas pressures of 7×10^{-2} mbar and annealed IGZO thin films, which of the energy band gaps were measured to be 3.05 eV (Chuang *et al*. 2008) and 3.45 eV (Lin *et al*. 2016), respectively. These values are compatible with the band gaps of IGZO thin films reported in literature (Lin *et al*. 2016, Chuang *et al*. 2008). As a result, in this study, the grown at room temperature under oxygen gas pressure of 7×10^{-2} mbar and non-annealed IGZO thin film, which were determined as n-type layer to form an IGZO/p-Si hetero-junction diode (for production where high processing temperatures are not required).

3.4. Ag/IGZO/p-Si/Al hetero-junction diodes electrical characteristics of in the dark and the illumination environment

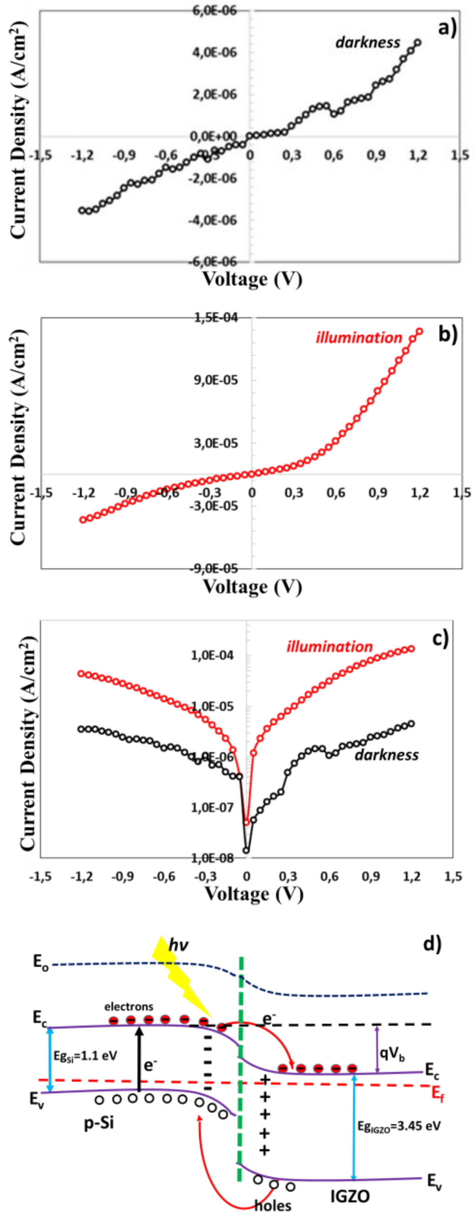


Figure 5. $J-V$ **a)** (in the darkness) and **b)** (under the illumination) **c)** the logarithmic $J-V$ curves of IGZO/p-Si hetero-junctions produced in oxygen gas pressure of 7×10^{-2} mbar in the darkness and under the illumination condition and **d)** IGZO/Si heterojunction' energy band diagram under the illumination

$J-V$ curves of IGZO/p-Si hetero-junction produced in oxygen gas pressure of 7×10^{-2} mbar in the darkness and under the illumination condition are shown in Fig 5. The rectification ratios (*RR*; the ratio of forward current to reverse current I_F/I_R) of IGZO/Si heterojunction diodes in darkness and under the illumination were determined to be $RR_{darkness}$=1.26 and $RR_{illumination}$=3.14, respectively. So, it has been observed that the hetero-junction diode exhibits a better rectifying behaviour in illumination condition (Chávez-Urbiola *et al*. 2019, Ismail *et al*. 2019). The electrons occupy in the valence band of p-Si that are excited by the photon, which transfer to its conduction band (in Fig 5c). Electrons in the conduction band of p-Si transfer the condition band of IGZO, which increase the photocurrent of the diode (Gezgin *et al*. 2020). The photocurrent to the dark current ratio (I_{ph}/I_{dark}) has calculated to be 12.25 at -1.2 V in reverse bias region.

A diode' current is expressed by Eq. (2) in thermionic emission theory,

$$I = I_0[exp(qV/nkT) - 1] \quad (2)$$

the forward bias voltage is expressed as V, the ideality factor is shown as *n*, the charge of electron is q. Boltzman constant is k, I_o is saturation current and the absolute temperature represent as T

A diode' ideality factor is stated by Eq. (3):

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

The forward bias current is displayed as I. n value is calculated and drawn in Fig 5b as the logarithmic $J - V$ characteristic. n values of IGZO/p-Si hetero-junction diodes in dark and under the illumination were determined to be $n_{darkness} = 6.07$ and $n_{illumination}$ =5.02, respectively. In both conditions, the ideality factors of the diodes are somewhat high. Furthermore, the ideality factor in darkness is higher than in the illumination (Rajeswari *et al*. 2020). Due to the amorphous structure of all IGZO thin film, SiO_x layer formed at the interface, an inhomogeneous interfaces, the disrupted carrier injections, heterogeneous distributions of interface charges, contact resistances, recombination in traps and defects, which lead to high ideality factor (Jing-Jing *et al*. 2010, Zhu *et al*. 2005, Gupta *et al*. 2009, Gupta *et al*. 2010, Bo *et al*. 2009, Zeyrek 2015).

Barrier height (Φ_b) for a diode is expressed by Eq. (4):

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

A and A* are expressed as the diode' active area and Richardson constant (32 A $cm^{-2}K^{-2}$ to p-Si)(Dhimmar, Desai, and Modi 2016), respectively. Φ_b value of IGZO/Si hetero-junction for the darkness and the illumination condition were obtained to be 0,71 eV and 0.65 eV, respectively. The barrier height has decreased for illumination condition (Bedia *et al*. 2013, Koksal *et al*. 2019). The transitions of photo exited minority charge carriers become easier in the depletion region.

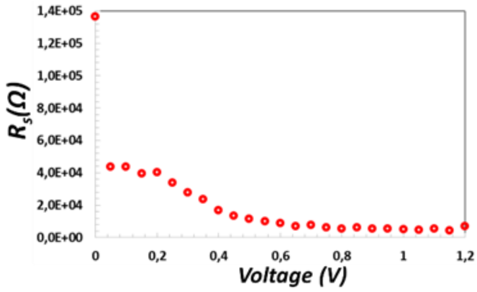


Figure 6. Serial resistance (R_s)-Voltage (*V*) curve of IGZO/p-Si diode to illumination condition

The series resistance (R_s) of a diode is an important parameter affecting its performance.It has been obtained that serial resistance-voltage curve of IGZO/p-Si hetero-junction diode under the illumination conditions were performed by using $R_s = \frac{\Delta V_{forward\ bias\ voltage}}{\Delta I_{forward\ bias\ current}}$ formula and is depicted in Fig 6. As the voltage was increased, the resistance was decreased and then stabilized at a certain value (Bedia *et al*. 2014, Soliman *et al*. 2008). Accordingly, R_s value of IGZO/p-Si diode is determined to be 4.32 kΩ. Series resistance is slightly higher that attributed to resistance of contacts, SiO_x layer at the interface of semiconductors, trapping of charge carriers in IGZO thin film and interface states.

The serial resistance, barrier height and ideality factor of a diode can be acquired by Cheung-Cheung method (Cheung and Cheung 1986) as well as the conventional $J - V$ method. Eq.(5), Eq.(6) and Eq.(7) define Cheung-Cheung method:

$$\frac{dV}{d(lnI)} = IR_s + n\left(\frac{kT}{q}\right) \quad (5)$$

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

$$H(I) = IR_s + n\Phi_b \tag{7}$$

Fig 7a and 7b indicate $dV/d(\ln J) - J$ and $H(J) - J$ curves of IGZO/Si hetero-junction diode taken under the illumination conditions. $dV/d(lnJ) - J$ characteristics in Fig 7a was acquired from Eq. (5). R_s and nkT/q are given by the slope and the y-axis intercept of $dV/d(\ln J) - J$ curves in Fig 7a, respectively. n values of IGZO/Si hetero junction diode have been obtained to be 5.29. R_s values of the hetero junction diode have been calculated to be 3.48 kΩ. The ideality factor and serial resistance values calculated by the conventional $J - V$ curve were found to be close to that of the values obtained by $dV/d(lnJ) - J$ curve (Orak *et al*. 2018).

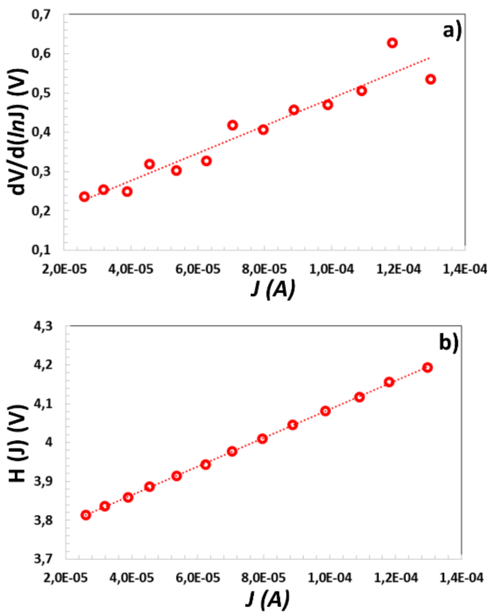


Figure 7. a) $dV/d(J) - J$ and **b)** $H(J) - J$ curve of IGZO/Si hetero junction diode under the illumination condition

$H(J) - J$ curve in Fig 7b have been obtained, using Eq (6). IR_s and $n\Phi_b$ in Eq. (7) are shown by the slope and the y-axis intercept in $H(J) - J$ curve, respectively. Φ_b value of IGZO/Si hetero-junction diode has been determined to be 0.70 eV. R_s value of IGZO/Si hetero-junction was obtained as 3.68 kΩ from Eq (7). Furthermore, R_s and barrier height values obtained from $dV/d(J) - J$, $H(J) - J$ and the conventional $J - V$ curves are relatively consistent with each other (Orak *et al*. 2018, Gezgin *et al*. 2020).

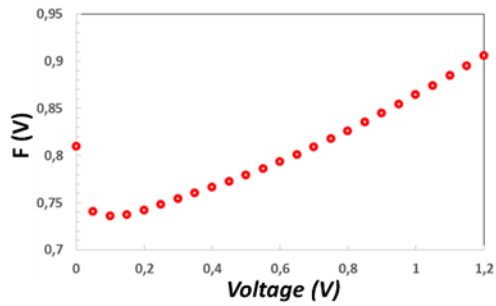


Figure 8. a) $F(V) - V$ curve of IGZO/Si hetero junction diode under the illumination condition

$F(V) - V$ curve of IGZO/Si hetero junction diode for illumination condition is given in Fig 8. The barrier height and serial resistivity of the diode were calculated using Norde method (Norde 1979). Norde method is shown by Eq. (8):

$$F(V,\gamma) = \frac{V}{\gamma} - \frac{kT}{q} ln\left(\frac{I(V)}{AA^*T^2}\right) \tag{8}$$

where γ is the first constant that is higher than n value acquired from log $J - V$ curve. Φ_b and R_s values can be determined by Norde method' equations:

$$\Phi_b = F(V_o) + \frac{V_o}{\gamma} - \frac{kT}{q} \tag{9}$$

$$R_s = \frac{\gamma - n}{I_{min}} \frac{kT}{q} \tag{10}$$

$F(V_o)$ is the value corresponding to the minimum spot of $F(V) - V$ characteristic, where V_o is voltage in the minimum $F(V_o)$ value, I_{min} shows the minimum voltage of $J - V$ curve. R_s values of IGZO/p-Si hetero junction diode has been determined to be 10.84 kΩ, and Φ_b values of these hetero-junction diodes have been calculated to be 0.63 eV, using Norde method' equations. R_s value were also acquired by Norde method, which is higher than that was determined by Cheung-Cheung method (Orak *et al*. 2018). This situation can be attributed to the fact that Norde method uses the whole forward bias region of log $J - V$ curve while Cheung-Cheung method contemplates just the nonlinear region in the forward bias (Orak *et al*. 2018, Basman 2017). As a result, n, R_s and Φ_b values calculated by the traditional $J - V$ method, Norde method and Cheung Cheung method, which were found to be close to each other for the illumination condition.

4. Conclusions

In this study, IGZO thin films were produced on p-Si wafer and SLG at low temperature, in oxygen gas pressure of 5×10^{-2} and 7×10^{-2} mbar, using PLD technique. IGZO thin films were formed in amorphous structure. As the pressure of oxygen gas increases, the size of the particles forming IGZO thin film increases and the thin film thickness decreases. The ideality factors and barrier heights of the produced IGZO/p-Si hetero junction diodes in oxygen gas pressure of 7×10^{-2} mbar to the darkness and illumination conditions; which were found as 6.07 and 0.71 eV; 5.02 and 0.65 eV, respectively. The electrical properties of IGZO/Si diode have been examined using the conventional $J-V$, Norde and Cheung Cheung methods to the illumination condition. n, R_s and Φ_b values of the hetero junction-diode calculated by these methods were found close to each other. As a result, IGZO/p-Si hetero junction diode produced at room temperature by PLD system can be used in UV detector application with low energy consumption.

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