

# The determination of electronic parameters of Al/MDMO-PPV/p-Si/Al Schottky diode by current–voltage characteristics

A. ASIMOV<sup>a</sup>, M. AHMETOGLU (AFRAILOV)<sup>a</sup>

<sup>a</sup>Department of Physics, Faculty of Sciences and Arts, Uludag University, 16059 Gorukle, Bursa, Turkey

Current–voltage (I–V) characteristics of Al/MDMO-PPV/p-Si (111) Schottky barrier diodes (SBDs) have been investigated at room temperature. Here, (MDMO-PPV) poly-[2-(3,7-dimethyloctyloxy)-5-methyloxy]-para-phenylene-vinylene has been used as interfacial layer between metal and semiconductor layers. The characteristic parameters of the structure such as barrier height, ideality factor, interface states density and series resistance were determined from the electrical measurements. Also, Cheung functions and Norde method were used to evaluate the I–V characteristics and to obtain the characteristic parameters of the Schottky contact. The diode parameters such as ideality factor, barrier heights and interface state density, series resistance were found as 1,73–1,93 and 0,89–0,79 eV and  $1,11 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$  at (1,09– $E_v$ ) eV to  $9,91 \times 10^{14} \text{ eV}^{-1} \text{ cm}^{-2}$  at (0,87– $E_v$ ) eV respectively. The series resistance  $R_s$  values were determined from  $dV/d \ln I$ – $I$  and  $H(I)$ – $I$  plots and were found to be  $9,2 \times 10^3 \text{ k}\Omega$  and  $10,1 \times 10^3 \text{ k}\Omega$  respectively

(Received October 24, 2013; accepted September 11, 2014)

**Keywords:** Schottky barrier diode, Ideality factor, Barrier height, Conducting polymers, MDMO-PPV

## 1. Introduction

In recent years, there has been growing interest in the field of metal/polymer/semiconductor (MPS) structures due to their successful application in optical and electronic devices [1–6]. These structures can be used at different in photonic and electronic device applications, such as organic solar cells, organic field effect transistors, organic light emitting diodes and photodetectors. Due to the technological importance of electrical characteristics of organic thin films is of greater interest. It is well known that the electrical characteristics of a Schottky diode are controlled mainly by its interface properties [4]. The interface states and polymeric interfacial layer in metal/polymer/semiconductor (MPS) structures play an important role on the determination of the main electrical and dielectric parameters of these devices [12]. Therefore, the interfacial parameters such as interface state density ( $N_{ss}$ ), the thickness of the interfacial layer and the Schottky barrier inhomogeneity at M/S interface give rise to masking of the real electrical characteristics of SBD [3–8]. Conducting polymers such as polypyrrole, polyaniline, MDMO-PPV, polythiophene (PTh) have been employed particularly in the metal-semiconductor devices due to their stability and rectifying behavior [6–11]. (MDMO-PPV) poly-[2-(3,7-dimethyloctyloxy)-5-methyloxy]-para-phenylene-vinylene has been one of the most studied conducting polymers because of its physical and electrical properties, ease and cheapness of fabrication.

The characteristic parameters of the Al/MDMO/p-Si/Al sandwich SBD were calculated using forward-bias current-voltage (I–V) measurements. The I–V measurements of the diode were carried out at room

temperature and in the dark. Some parameters which are such as ideality factor, barrier height, and series resistance influence the performance of the device. These parameters give useful information concerned with the nature of the diode. Also, the energy distribution profile of  $N_{ss}$  of the structure has been obtained from the forward bias I–V data by taking the bias voltage dependence of the effective  $BH(\Phi_e)$  and  $n$  at room temperature.

## 2. Experimental procedures

The properties of the semiconductor wafer (p-Si) used in this study have (100) orientation and 280 mm thickness. Before making contacts the p-Si was chemically cleaned using the RCA cleaning procedure. The RCA cleaning by procedure was as follows: to remove the native oxide layer, the wafer was dipped 10 min in  $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$  then 10 min in  $\text{HCl} + \text{H}_2\text{O}_2 + 6\text{H}_2\text{O}$ . Finally, it was immersed in diluted 20% HF for 60 s. The wafer was rinsed in de-ionized water of resistivity 18  $\text{M}\Omega \text{ cm}$  with ultrasonic cleaning in each step. Finally, the sample was dried by exposing the surfaces to high-purity nitrogen. The ohmic contact with a thickness of  $\sim 1650 \text{ \AA}$  was made by evaporating 99.9% purity Al metal on the back surface of the p-Si substrate, then was annealed at 550 °C for 3 min in  $\text{N}_2$  atmosphere. Front surface of samples were coated with a conducting polymer (MDMO-PPV) Fig. 1. film by spin coating (VTC-100) with 1200 rpm for 60 s. After that rectifier Schottky contacts were formed on the other faces by evaporating  $\sim 2000 \text{ \AA}$  thick Al. Thus, Al/poly-[2-(3,7-dimethyloctyloxy)-5-methyloxy]-para-phenylene-vinylene (MDMO-PPV)/p-Si/Al sandwich Schottky

barrier diode was obtained. The evaporation process was carried out in a vacuum of  $5,1 \times 10^{-6}$  Torr. The current–voltage (I–V) characteristics have been measured using a Keithley 6517 Electrometer at room temperature and in the dark. All measurements were controlled a computer via an IEEE—488 standard interfaces so that the data collecting processing and plotting could be accomplished automatically.

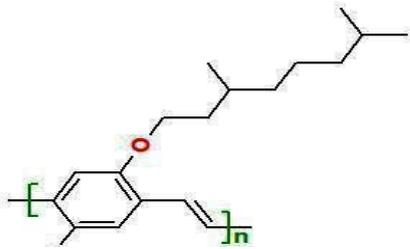


Fig. 1. Molecular structure of MDMO-PPV.

### 3. Results and discussion

#### 3.1. Current–voltage characteristics of Al/MDMO-PPV/p-Si Schottky barrier diode

The forward and reverse bias I–V characteristics of the Al/MDMO-PPV/p-Si contact at room temperature are given in Fig. 2.

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

where  $I$  is the measured current,  $V$  is the applied voltage,  $q$  is the electronic charge,  $n$  is the ideality factor that describes the deviation from the ideal diode equation for reverse bias as well as forward bias,  $k$  is the Boltzmann's constant,  $T$  is the absolute temperature in Kelvin,  $I_0$  is the saturation current derived from the straight line intercept of  $\ln I$  at zero-bias and is given by

$$I_0 = AA^*T^2 \exp\left(-\frac{q\phi_{B0}}{kT}\right) \quad (2)$$

where  $q$  is the electronic charge,  $T$  is the temperature in K,  $A^*$  is the effective Richardson constant and equals  $32 \text{ A cm}^{-2}\text{K}^{-2}$  for p-type Si [14],  $A$  the effective diode area,  $k$  is the Boltzmann constant,  $\phi_{B0}$  (I–V) is the zero bias barrier height and  $n$  is the ideality factor. From Eq. (1), ideality factor  $n$  can be written as

$$n = \frac{q}{kT} \left(\frac{dV}{d(\ln I)}\right) \quad (3)$$

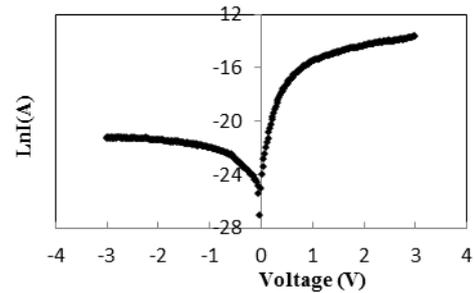


Fig. 2. Experimental forward and reverse bias  $\ln I$ – $V$  characteristics of the Al/MDMO-PPV/p-Si Schottky diode.

$n$  equals to one for an ideal diode. However,  $n$  may be a value greater than unity. Fig. 2 shows a semi-logarithmic plot of the forward bias I–V characteristics of the Al/MDMO/p-Si/Al structure at room temperature. The ideality factor value of Al/MDMO/p-Si/Al Schottky diode was calculated using Eq. (3) from the linear region of the forward bias I–V plots and was found to be 1,73. The high value of  $n$  compared with the unity ( $n = 1$ ) for the ideality factor indicates the presence of an interfacial layer (a native oxide layer) at the MDMO-PPV and Si interface.

$$\phi_{B0} = \frac{kT}{q} \ln\left(\frac{AA^*T^2}{I_0}\right) \quad (4)$$

The value of barrier height of Al/MDMO/p-Si/Al Schottky diode was found to be 0.89 eV, from the y-axis intercept of the semilog-forward bias I–V plots with the help of Eq. (4). Some studies have been made for tuning Schottky barrier heights by organic modification of Al/p-Si contacts [18–27]. Al/p-Si Schottky diodes with the polymer (polyaniline) interfacial layer have been prepared by Aydoğan et al. [20] and the zero bias barrierheight and ideality factor for these diodes were determined as 0.68 eV and 1.38, respectively. Aydin et al.[18] were published a paper about Al/MEH-PPV/p-Si diode with the zero bias barrier height value of 0.80 eV and ideality factor value of 1.88. The zero bias barrier height of 0.75 eV and the ideality factor of 1.47 values for Al/new fuchsin/p-Si Schottky diodes were determined from I–V measurements by Güllü et al. [19]. These studies suggest that the organic layer between metal and semiconductor causes the barrier enhancement because the barrier height values reported by these authors are larger than those obtained for conventional Al/p-Si. Our value of the barrier height is in close agreement with those reported by some authors for Al/insulator layer/ p-Si and Al/organic layer/p-Si [20] and it is larger than those obtained for conventional Al/p-Si [19–20] as in literature.

The forward bias I–V characteristics of the Schottky diodes might be deviated considerably from linearity due to the some factors at the higher voltage region. The series resistance is an important parameter for electrical

characteristics of Schottky barrier diodes. This parameter is influenced by the presence of the interface layer between the metal and the semiconductor and leads to non-ideal forward-bias current–voltage. The series resistance can be evaluated using a method developed by Cheung and Cheung [15] and this method also allows one to find Schottky diode parameters such as the barrier height, the ideality factor, and the series resistance. Cheung’s functions can be written as follows:

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

$$H(I) = V - n\left(\frac{kT}{q}\right) \ln\left(\frac{I_0}{AA * T^2}\right) \quad (6)$$

$$H(I) = IR_s + n\Phi_b \quad (7)$$

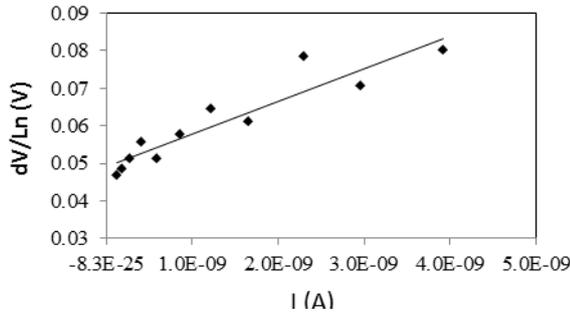


Fig. 3. Plot of  $dV/d\ln(I)$ – $I$  of Al/MDMO-PPV/p–Si Schottky barrier diode at room temperatures.

Eq. (5) should give a straight line for the data in the downward-curvature region of the forward bias I–V characteristics, where  $\Phi_b$  is the BH obtained from data of downward-curvature region in the forward bias I–V characteristics. The value of  $n$  calculated from the slope of the linear portion of the I–V characteristics especially includes the effect of the interfacial parameters such as  $n$  and  $R_s$  let us obtain the functions of Cheung and Cheung [15]. The values of  $n$  and  $R_s$  were calculated as 1,93 and  $9,2 \times 10^3$  k $\Omega$  from the intercept and the slope of Fig. 3, respectively. The values of  $\Phi_b$  and  $R_s$  were calculated as 0.79 eV and  $10,1 \times 10^3$  k $\Omega$  from the intercept and the slope of Fig. 4, respectively. Because of the non-linearity of the I–V characteristics, the values of the ideality factor obtained from Cheung's functions can be higher than the values from the forward-bias I–V characteristics. The difference between the values of the ideality factors can be attributed to the fact that the first one only under the effect of the interfacial properties and the second one is under the effect of both the interfacial properties and the series resistance.

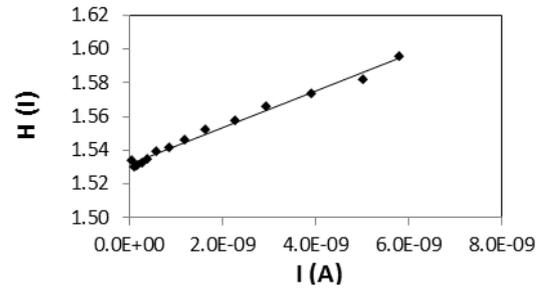


Fig. 4. Plot of  $H(I)$ – $I$  of Al/MDMO-PPV/p–Si Schottky barrier diode at room temperatures.

Furthermore, the values of barrier height and series resistance of the device have been evaluated by the analysis of Norde’s method [16]. The following function has been defined in the modified Norde’s method:

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

where  $\gamma$  is the first integer (dimensionless) greater than  $n$ . That is, according to our results, the value of  $\gamma$  is 2.  $I(V)$  is current obtained from the I–V curve. Once the minimum of the  $F$  versus  $V$  plot is determined, the value of barrier height can be obtained from Eq.(9).

$$\Phi_B = F(V_0) + \frac{V_0}{2} - \frac{kT}{q} \quad (9)$$

where  $F(V_0)$  is the minimum point of  $F(V)$  and  $V_0$  is the corresponding voltage. Fig. 5 shows the  $F(V)$ – $V$  plots of the device. The value of the series resistance has been obtained from Norde’s method by using Eq. (9):

$$R = \frac{kT(\gamma - n)}{qI_0} \quad (10)$$

from the  $F$ – $V$  plot, the some parameters of the structure have been determined as  $\Phi_b = 1,17$  eV,  $R_s = 2,72 \times 10^3$  k $\Omega$  using  $F(V_0) = 0,75$  eV,  $V_0 = 0,41$  V values. The value of the series resistance obtained from Cheung's functions is lower than the values obtained from Norde's functions. Cheung functions are only applied to the non-linear region in high voltage region of the forward-bias  $\ln$  I–V characteristics. But, Norde’s functions are applied to the full forward-bias region of the  $\ln$  I–V characteristics of the junctions. The  $R_s$  value for the diode was determined using Eq.(10) and was found to be  $2,72 \times 10^3$  k $\Omega$ . This is considerable higher due to the interfacial states and series resistance and the film properties of conducting polymer MDMO-PPV. This causes a non-linear region of forward bias I–V curve of the diode

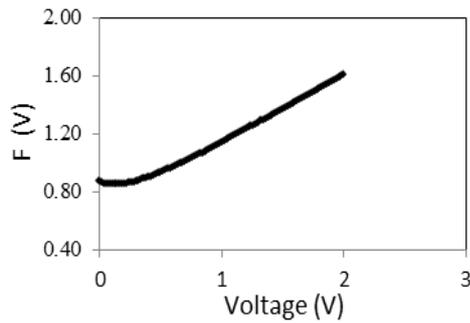


Fig. 5.  $F(V)$  vs.  $V$  plot of Al/MDMO-PPV/p-Si structure.

The interface states between the organic semiconductor compound and inorganic semiconductor play an important role in the determination of the characteristic parameters of the devices. The density of the interface state proposed by Card and Rhoderick [23] is given by

$$N_{ss}(V) = \frac{1}{q} \left\{ \frac{\epsilon_i}{\delta} [n(V) - 1] - \frac{\epsilon_s}{W_D} \right\} \quad (11)$$

where  $N_{ss}$  is the density of the interface states,  $\delta$  is the thickness of interfacial layer,  $W_d$  is the space charge width,  $\epsilon_s = 11.8\epsilon_0$  and  $\epsilon_i = 3.8\epsilon_0$  are the permittivity of the semiconductor and interfacial layer, respectively. Furthermore, in p-type semiconductor, the energy of interface states,  $N_{ss}$  with respect to the bottom of the valence band  $E_v$  at the surface of the semiconductor is given by

$$E_{ss} - E_v = q(\Phi_e - V_D) \quad (12)$$

where  $\Phi_e$  is the effective barrier height,  $N_{ss}$  values are obtained via Eq.(10). The energy distribution of the interface states is determined from experimental data of this region of the forward bias I-V and this is seen in Fig. 6. The  $N_{ss}$  value decreases with increasing  $E_{ss} - E_v$  value. The energy distribution curve of the interface state density ( $N_{ss}$ ) ranges from  $1.11 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$  at  $(1.09 - E_v)$  eV to  $9.91 \times 10^{14} \text{ eV}^{-1} \text{ cm}^{-2}$  at  $(0.87 - E_v)$  eV for Al/MDMO-PPV/p-Si Schottky diode as given Fig. 6. The interface states and interfacial layer between the polymeric organic compound/semiconductor structures play an important role in the determination of the characteristic parameters of the devices. The presence of the interface layer, interface states and fixed surface charge causes the reverse bias and forward bias characteristics of Schottky devices not to obey the ideal Schottky diode characteristics. Therefore, it can be said that the performance and reliability of Schottky devices depend on the interface layer and fixed surface charge. Briefly, polymeric organic/inorganic semiconductor diodes may be useful to increase the quality of devices fabricated by using the semiconductor in establishing processes for minimizing surface states,

surface damage and contamination and actively tunable barrier heights [22].

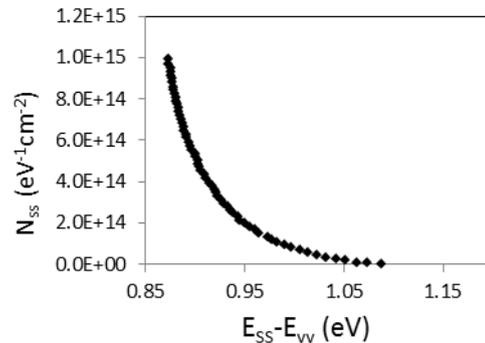


Fig. 6. Density of interface states  $N_{ss}$  as a functions of  $E_{ss} - E_v$  obtained from the I-V measurements at room temperature.

#### 4. Conclusion

Electrical properties of the Al/MDMO-PPV/p-Si Schottky barrier diodes (SBDs) have been investigated by using I-V measurements at room temperature. The electronic parameters such as ideality factor, barrier height and series resistance of the Schottky diode were extracted by forward-bias I-V, Cheung's functions and Norde's functions. The Schottky diode parameters such as ideality factor, and barrier height were found as 1,73-1,93 and 0.89-0,79 eV respectively. The series resistance  $R_s$  values were determined from  $dV/d \ln I-I$  and  $H(I)-I$  plots and were found to be  $9,2 \times 10^3 \text{ k}\Omega$  and  $10,1 \times 10^3 \text{ k}\Omega$  respectively. The high resistance values have given the high ideality factors. There is a good agreement with the values of barrier height obtained from all methods. Also, the energy of interface states was determined from the forward-bias I-V data. The interface state density decreases exponentially with bias from  $9,91 \times 10^{14} \text{ eV}^{-1} \text{ cm}^{-2}$  at  $(0,87 - E_v)$  eV to  $1,11 \times 10^{12} \text{ eV}^{-1} \text{ cm}^{-2}$  at  $(1,09 - E_v)$  eV

#### References

- [1] E. H. Rhoderick, R. H. Williams, Metal-Semiconductor Contacts, Clarendon, Oxford, 1988.
- [2] A. Trt, F. Kleli, J. Appl. Phys. **72**, 818 (1992).
- [3] T. Tun, Ő. Altndal, İ. Dkme, H. Uslu, J. Electron. Mater. **40**(2), 157 (2011).
- [4] H. C. Card, E. H. Rhoderick, J. Phys. D: Appl. Phys. **4**, 1589 (1971).
- [5] M. Ahmetoglu (Afrailov), A. Kara, N. Tekin, S. Beyaz, H. Kokar, Thin Solid Films, **529**, 2105 (2012).
- [6] A. F. zdemir, D. A. Aldemir, A. Kke, Ő. Altndal, Synth. Met. **158**, 1427 (2009).
- [7] M. Ahmetoglu, A. Tekgul, M. Alper, B. Kucur, J.

- Optoelectron. Adv. Mater., **6**(1-2), 304 (2012).
- [8] M. Ahmetoglu (Afrailov), K. Erturk, J. Optoelectron. Adv. Mater. **10**(2), 298 (2008).
- [9] I. Musa, W. Eccleston, Thin Solid Films **343**, 469 (1999).
- [10] G. Liang, T. Cui, K. Varahramyan, Solid State Electron. **47**, 691 (2003).
- [11] R. K. Gupta, R. A. Singh, Mater. Chem. Phys. **86**, 279 (2004).
- [12] F. Nastase, I. Stamatina, C. Nastase, D. Mihaiescu, A. Moldovan, Prog. Solid State Chem. **34**, 191 (2006).
- [13] A. F. Özdemir, A. Gök, A. Türüt, Thin Solid Films **515**, 7253 (2007).
- [14] M. Gökçen, T. Tunç, Ş. Altındal, I. Uslu, Curr. Appl. Phys. **12**, 525e530 (2012).
- [15] S. K. Cheung, N.W. Cheung, Appl Phys Lett. **49**, 85 (1986).
- [16] H. Norde, J. Appl. Phys. **50**, 5052 (1979).
- [17] Ş. Altındal, H. Kanbur, D. E. Yıldız, M. Parlak, Appl. Surf. Sci. **253**, 5056 (2007).
- [18] M. E. Aydın, F. Yakuphanoglu, J. Eomc, D. Hwang, Physica B **387**, 239 (2007).
- [19] Ö. Güllü, T. Kilicoglu, M. Biber, A. Türüt, J. Phys. Condens. Matter **20**, 215520 (2008).
- [20] Ş. Aydoğan, M. Sağlam, A. Türüt, Microelectron. Eng. **85**, 278 (2008).
- [21] B. L. Smith, E. H. Rhoderick, Solid State Electron. **14**, 71 (1971).
- [22] F. F. So, S. R. Forrest, J. Appl. Phys. **63**(2), 442 (1988).
- [23] H. C. Card, E. H. Rhoderick, J. Phys. D: Appl. Phys. **4**(10), 1589 (1971).
- [24] Ş. Aydoğan, M. Sağlam, A. Türüt, Microelectron. Eng. **85**(2), 278 (2008).
- [25] F. Yakuphanoglu, Solar Energy Mater. Solar Cells **91**(13), 1182 (2007).
- [26] M. E. Aydın, F. Yakuphanoglu, J. Eomc, D. Hwang, Phys. B **387**(1–2), 239 (2007).
- [27] M. Sağlam, D. Korucu, A. Türüt, Polymer **45**, 7335 (2004).

---

\*Corresponding author: afrailov@uludag.edu.tr