Physica E 41 (2009) 631–634

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Extraction of electronic parameters of Schottky diode based on an organic semiconductor methyl-red

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ARTICLE INFO

Article history:
Received 3 August 2008
Accepted 6 August 2008
Available online 24 November 2008

PACS:
07.50.−e
87.15.Pc

Keywords:
Schottky diodes
Series resistance
Ideality factor
Barrier height

ABSTRACT

The current–voltage (*I–V*) characteristics of Al/methyl-red/Ag surface-type structure were investigated in air at room temperature. The conventional forward bias *I–V* method, Cheung functions and modified Norde's function were used to extract the diode parameters including ideality factor, barrier height and series resistance. The parameter values obtained from these three different methods were found in good agreement.

1. Introduction

Schottky diodes are playing an important role in modern electronics. Although Schottky diodes have the simplest structure, they are the base of a large number compound semiconductor electronic devices [1,2]. Schottky diodes have unique advantages over p–n junction diodes due to fast response, low resistance and very small transient reverse current during switching [3,4]. Additionally, the reverse saturation current of Schottky barrier diodes is higher than the conventional p–n junction diodes [5]. Therefore, a Schottky diode needs low forward bias voltage to achieve a given current compared to a p–n junction diode. The performance of Schottky barrier diodes depends upon the characteristics of the metal/semiconductor junction. Therefore, the understanding of electrical properties of interface between metal and organic layer is important for device applications. There are many factors that can affect the properties of the junction. These factors include the effects of series resistance (R_s), formation of barrier height, insulating layer between metal and semiconductor, and interface states. It is well known that the surfaces of most metals are covered by oxide layer when placed in open air environment. The insulator layer between metal–semiconductor diodes have a strong influence on the diode characteristics [6–8]. Due to these reasons, the experiments performed on Schottky diodes often show a non-ideal behavior of the *I–V* characteristics [9,10].

Very recently, some authors [11,12] investigated Schottky diodes fabricated using non-polymeric organic compound and reported that the non-polymeric organic materials are very suitable for electronic devices mainly due to their stability [12–14]. The non-polymeric compound methyl-red used in this work is an organic semiconductor in the form of dark red crystalline powder. The heterojunctions of methyl-red with p-silicon were investigated in Refs. [11,15,16]. The humidity sensing properties of methyl-red in surface-type cell and its electrical properties in surface-type Schottky diode were studied by us [17,18]. These studies showed the potential of methyl-red for the application in electronic devices.

In this work, the non-polymeric organic compound methyl-red is chosen for the fabrication of the Al/methyl-red/Ag surface-type Schottky diode due to its conjugated structure, stability [11] and richness in 16-π-electron [19]. The aim of this investigation is to extract the parameters that control the device performance such as barrier height, ideality factor and series resistance from *I–V* characteristics by using different methods at room temperature.

2. Sample preparation

Methyl-red with molecular formula $C_{15}H_{15}N_3O_2$ purchased from Sigma Aldrich was used for the fabrication of the Al/methyl-red/Ag surface-type Schottky diode. The molecular structure of

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doi:10.1016/j.physe.2008.08.068

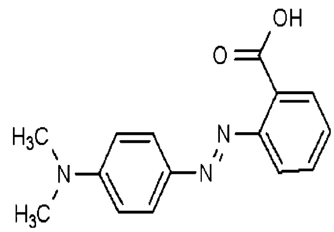

Fig. 1. Molecular structure of methyl-red.

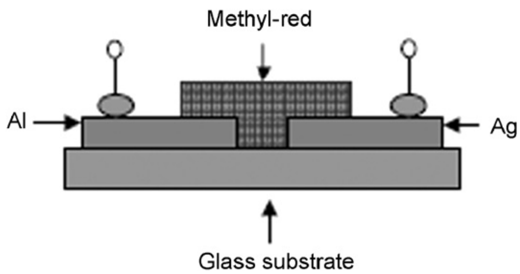

Fig. 2. Cross-sectional view of Al/methyl-red/Ag surface-type Schottky diode.

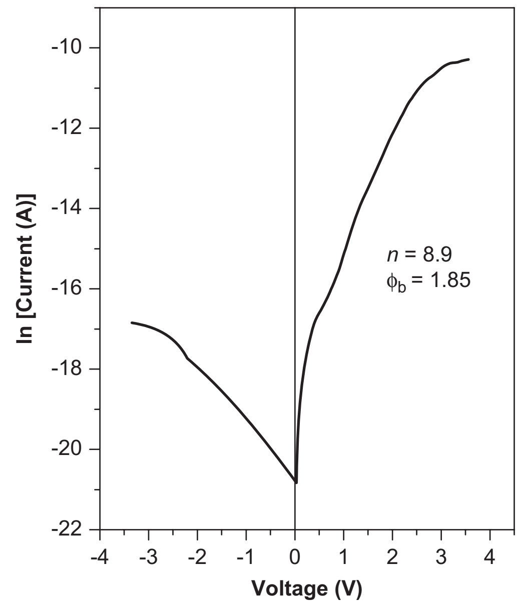

Fig. 3. Semi-log I–V curve of Al/methyl-red/Ag Schottky diode.

the methyl-red is shown in Fig. 1. A 10 wt% solution of methyl-red was prepared in benzene. The solution was stirred for 2 h at room temperature to make it homogeneous. The glass substrate was cleaned for 10 min using distilled water in an ultrasonic cleaner and after drying, the substrate was plasma cleaned for 5 min followed by the thermal deposition of Al and Ag electrodes by using a mask. During thermal deposition the chamber pressure was 5.5×10^{-5} mbar while the deposition rate was kept at 0.1 nm/s. The thickness of the electrodes was 100 nm and gap between the electrodes was 30 μm. The length of the gap was 17 mm. After that the thin film of methyl-red was deposited by spin coating with an angular rotation of 2000 rpm. The thickness of methyl-red film was 300 nm. The fabricated device was kept at 50 °C for 1 h to let the moisture in the film evaporate. Cross-sectional view of Al/methyl-red/Ag surface-type Schottky diode is shown in Fig. 2. Functional testings were made on a Karl Suss PM 5 probe station. The measurements were taken by using current–voltage source keithley-228A and by using keithley-196system DMM.

3. Results and discussion

The forward- and reverse-biased semi-log I–V characteristics of the Al/methyl-red/Ag surface Schottky barrier diode at room temperature are exhibited in Fig. 3. In forward bias, the Al contact was positively biased and the Ag was negatively biased. The I–V characteristics of the Al/methyl-red/Ag surface Schottky barrier diode showed rectification behavior which is limited by the magnitude of the energy barrier at the junction interface [11]. The rectification ratio was found to be 200 at ± 4 V. The rectification ratio is the ratio of forward current to reverse current at certain voltage. It is assumed that the current in the Schottky contact is due to thermionic emission. According to the thermionic emission theory, the current in Schottky barrier diodes can be expressed as [20]

$$I = I_o \exp\left(\frac{qv}{nkT}\right)\left[1 - \exp\left(-\frac{qv}{nkT}\right)\right] \tag{1}$$

where I_o is the reverse saturation current and can be expressed as

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

where V is the applied voltage, A is the effective diode area ($1.7 \times 10^{-9}\,\mathrm{m}^2$), A^* is the effective Richardson constant ($102\,\mathrm{A/cm^2\,K^2}$, taken from Richardson's law), ϕ_b is the effective barrier height at zero bias, k is the Boltzmann constant. T is the temperature in Kelvin and n is the ideality factor. The value of reverse saturation current obtained from forward bias semi-log I–V curve was 5.6×10^{-9} A. The value of ideality factor n can be calculated, from the slope of the linear region of the forward bias $\ln I$–V plot by using the following relation:

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

By using the above equation the value of ideality factor was calculated to be 8.9. For ideal diode the value $n = 1$. However, usually n has a value higher than unity. High values of ideality factor can be attributed to the presence of native oxide layer on electrodes and non-homogenous barrier [1,21,22]. The high values of ideality factor may also be due to possibly other effects, such as non-homogeneous thickness of organic film, organic layer effect, etc. The value of zero bias barrier height was found to be 1.8 eV, which was calculated by using Eq. (2).

Forward bias I–V characteristic are linear in semi-log scale at low voltage, but at higher voltages the characteristics deviate from linear behavior. It is well known, the curvature of the forward biased I–V plots at higher voltages is due to the R_S, apart from the effect of interface traps distribution, which are in equilibrium with the semiconductor materials [23]. If the effect of series resistance is less, then the nonlinear region of forward bias I–V curve will be small [24]. From the non linearity of semi-log I–V curve of Al/methyl-red/Ag Schottky diode at higher voltage, the value of series resistance was found 41.8 kΩ.

To determine the electronic parameter of the Schottky diode the second method, which is known as Cheung and Cheung method is used [25]. According to this method the forward bias I–V characteristics due to the thermionic emission with the effect of series resistance can be written as

$$I = I_o \exp\left[\frac{q(V - IR_S)}{nkT}\right] \tag{4}$$

where IR_S is the voltage drop across the series resistance. According to Cheung and Cheung the values of series resistance, ideality factor and barrier can be determined from following functions and by using Eq. (4):

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

and

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

$$H(I) = IR_S - n\phi_b \quad (7)$$

where the factor IR_S is the voltage drop across the series resistance of the diode. The values of series resistance and $n(kT/q)$ are obtained from the slope and y-axis intercept of the graph $dV/d(\ln I)$ vs. I. Similarly, the plot of $H(I)$ vs. I gives a straight line with the y-axis intercept equal to $n\phi_b$. The slope of this plot also gives the value of series resistance by which the consistency of Cheung's approach can be checked. The graphs of $dV/d(\ln I)$ vs. I and $H(I)$ vs. I are shown in Figs. 4 and 5, respectively. The determined values of series resistance from the plots of $dV/d(\ln I)$ vs. I and $H(I)$ vs. I were found to be 42.7 and 44 kΩ, respectively. The average value of series resistance for the Schottky diode was found to be 43.35 kΩ. As it can be seen that the values of series resistance from the Cheung plots $dV/d(\ln I)$ vs. I and $H(I)$ vs. I are in good agreement with each other and also with the value obtained from semi-log I–V curve.

Moreover, to understand mechanisms which can control the behavior of the Schottky diode, I–V characteristic of the device is plotted in log scale shown in Fig. 6. This double logarithmic graph of the diode in forward bias shows that the charge transport in the device is mainly governed by space–charge-limited current (SCLC) model. The double logarithmic graph also shows the power law behavior of the current ($I \propto V^{m+1}$) with different values of exponent (m+1). Thus, the transport through the methyl-red thin film is governed by the trapped–charge-limited current (TCLC) in the band gap of the methyl-red. This means, when the density of injected free charge carriers is much greater than the thermally generated free carriers, then the SCLC conduction should be dominant.

It is clear from Fig. 6 that the forward bias double log I–V characteristics show three distinct linear regions separated by transition segments. The first region is ohmic with slope about unity up to a transition voltage of about 0.8 V, which obeys the equation $J = q\mu n_o V/d$, where n_o is the concentration of the free charge carriers in the methyl-red film, μ is the mobility of charge carrier in the film and d is the thickness of the film. The second region of this graph having a slope of 5 up to a transition voltage of about 2.7 V is similar to the SCLC with the exponential distribution of traps in the band gap of the organic material. According to this model the trap charge limited current dominates the organic semiconductor methyl-red at high injection. The third region of double logarithmic forward bias curve has a slope value of 1.4. This region shows that at higher voltages the slope of the curve decreases because the device approaches the trap filled limit. When the injection level is high the behavior of this region is same as in trap free SCLC [16,26,27].

Beside the conventional I–V method and Cheung functions, there is another method to determine the value of series resistance, which was proposed by Norde and known as Norde's Method. The following equation has been used to express the

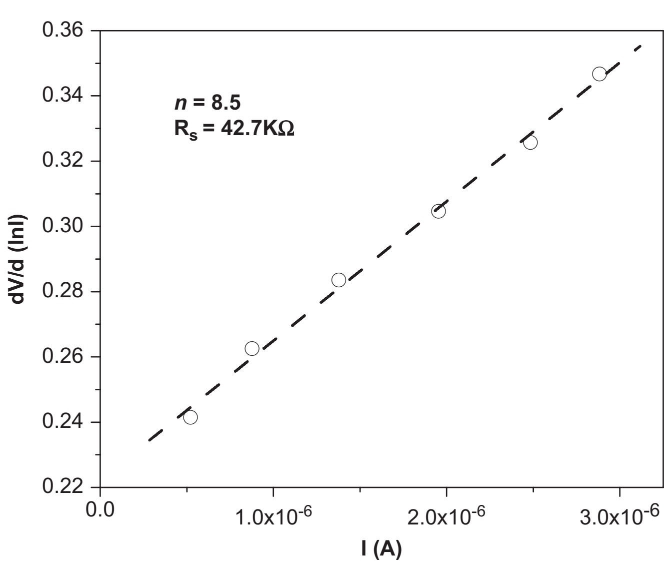

Fig. 4. $dv/d(\ln I)$–I plot of Al/methyl-red/Ag Schottky diode.

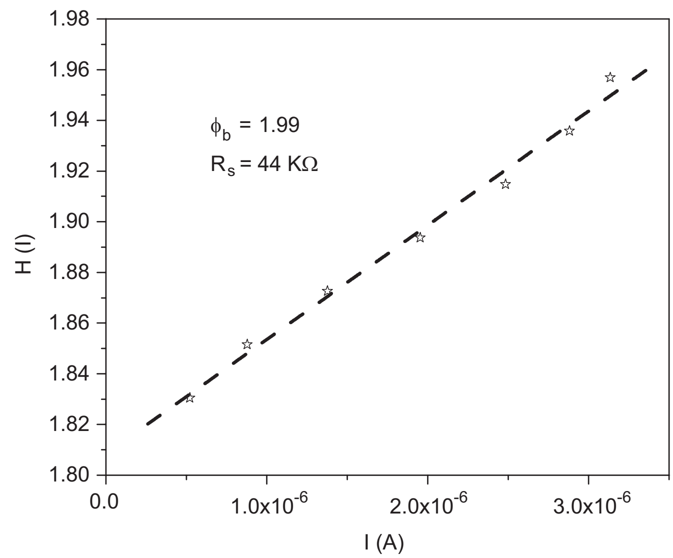

Fig. 5. $H(I)$–I plot of Al/methyl-red/Ag Schottky diode.

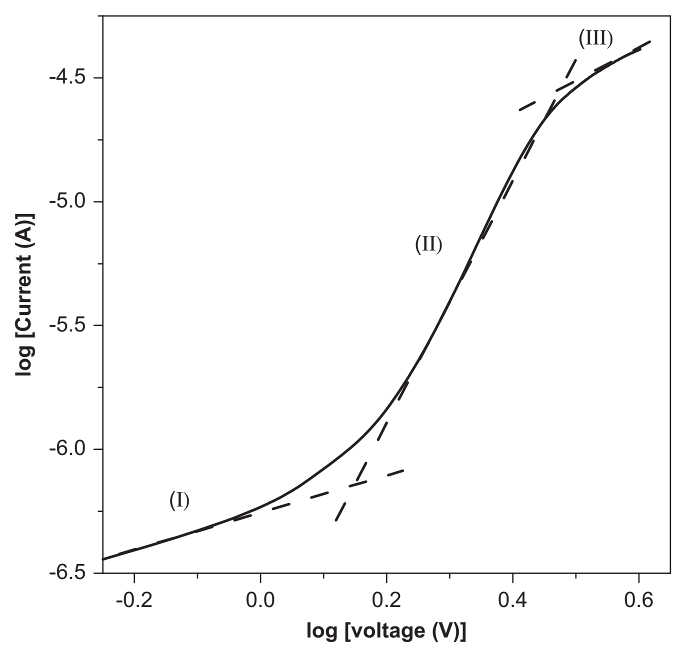

Fig. 6. The forward bias log(I) vs. log(V) plot.

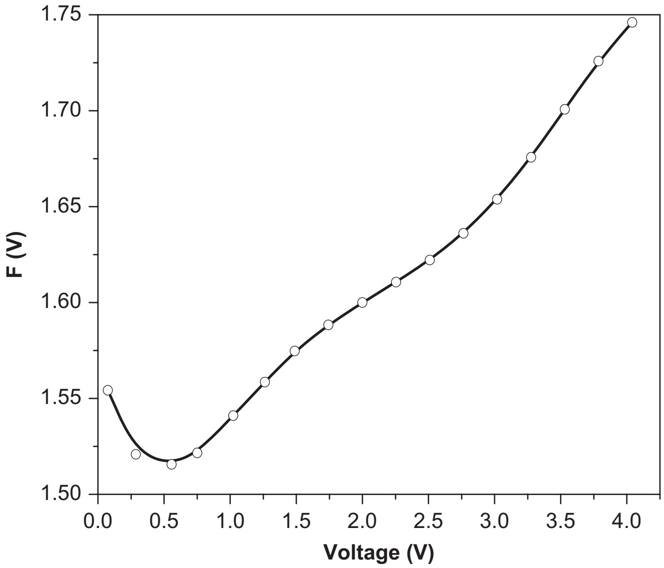

Fig. 7. $F(V)$ vs. V plot of Al/methyl-red/Ag Schottky diode.

Table 1
Experimentally obtained values of barrier height, series resistance and ideality factor.

	Barrier height (eV)	Series resistance (kΩ)	Ideality factor
Semi-log I–V	1.8	41.8	8.9
$dV/d(\ln I)$ vs. I plot	–	42.7	8.6
$H(I)$ vs. I plot	1.99	44	–
Norde's function	1.76	48.73	–

modified Norde's method [28,29].

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

where γ is dimensionless (the first integer) having value larger than n. In this case, its value is taken as 10. The $I(V)$ is value of current taken from the I–V curve. If the minimum of the $F(V)$ vs. V plot is found then the barrier height can be calculated by using the following equation:

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

$F(V_o)$ is the minimum value of $F(V)$, and V_o is the corresponding voltage. The Norde plot for Al/methyl-red/Ag surface-type Schottky diode is shown in Fig. 7. The value of the series resistance has been calculated from Norde's function for Al/methyl-red/Ag Schottky diode junction by using the following relation:

$$R_S = \frac{kT(\gamma - n)}{qI} \tag{10}$$

By using Norde's method, the values of series resistance and barrier height were obtained as 48.73 kΩ and 1.76 eV, respectively. We can see from Table 1 that the values of Schottky diode parameters obtained from the different methods show good agreement.

4. Conclusion

In conclusion, we have fabricated surface-type Al/methyl-red/Ag Schottky barrier diode. The electronic parameters such as ideality factor, barrier height and series resistance of the diode were extracted by three methods. The parameters obtained by using different methods are in good agreement.

Acknowledgements

The authors are thankful to the *Ghulam Ishaq Khan Institute of Engineering Sciences and Technology* (www.giki.edu.pk) for its support during this work. We are pleased to acknowledge the *Higher Education Commission* (*HEC*) *Pakistan* for providing Ph.D. scholarship to Mr. Zubair Ahmad.

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