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Electrical properties and *I–V* characteristics of 5,14-dihydro-5,7,12,14-tetraazapentacene doped Schottky barrier diode

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Abstract The current–voltage (*I–V*) characteristics of Aluminium/5,14-dihydro-5,7,12,14-tetraazapentacenes (L5H2 or DHTAPs) doped surface-type structures were investigated in air at ambient temperature and moisture. The conventional forward bias *I–V* method, Semi-logarithm, Cheung functions and modified Norde's function were used to extract the diode parameters including ideality factor, series resistance and barrier height. The parameter values obtained from these four different methods were found in good agreement.

Keywords Schottky diodes · 5,14-dihydro-5,7,12,14-tetraazapentacenes (L5H2 or DHTAPs) doped · Series resistance · Ideality factor · Barrier height

Introduction

The large range of electronic and optical properties of organic conducting polymers makes them very good candidates for use in modern electronic devices. The fabrication of electronic devices based on conducting polymers, especially Schottky diodes, can be simple and of low cost compared with devices based on inorganic semiconductors. The photoelectrical properties of metal–semiconductor (MS)—have been studied as photovoltaic cells, photodiodes and Schottky diodes by a number of authors [1–22]. Schottky diodes are playing an important role in modern electronic devices. Although Schottky diodes have the simplest structure, they are the base of a great number of compound semiconductor electronic devices [23, 24]. Schottky diodes are less expensive to fabricate than p–n junction diodes and the device performance is better due to faster response, low resistance, very small transient reverse current during switching and the reverse saturation current of Schottky barrier diodes is higher than that of the conventional p–n junction diodes [25–27]. The Schottky diode requires lower forward bias voltage to deliver a given current compared to a p–n junction diodes. The operation of Schottky barrier diodes relies upon the device characteristics of the MS junction. Therefore, the understanding of the electronic properties of the surface between metal and the organic layer is important for device applications. Series resistance (R_s), formation of Schottky barrier, insulating layer between metal and semiconductor and also the interface states can affect the properties of the junction.

Recently, a number of authors [28] investigated Schottky diodes fabricated using non-polymeric organic and oligomer compounds have reported that the non-polymeric organic materials are suitable for electronic devices, especially Schottky diodes, mainly due to their stability [28–30]. The compound, 5,14-dihydro-5,7,12,14-tetraazapentacenes (L5H2) used in this work is a doped organic semiconductor in the form of dark blue powder. The heterojunctions of L5H2 have been investigated in Ref. [31]. These studies showed the potential of L5H2 for the application in electronic devices.

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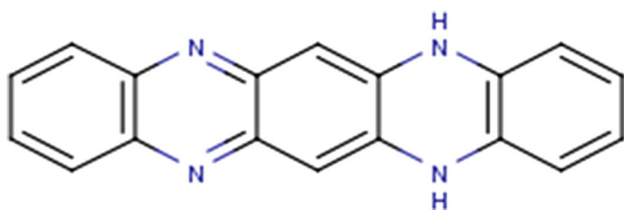
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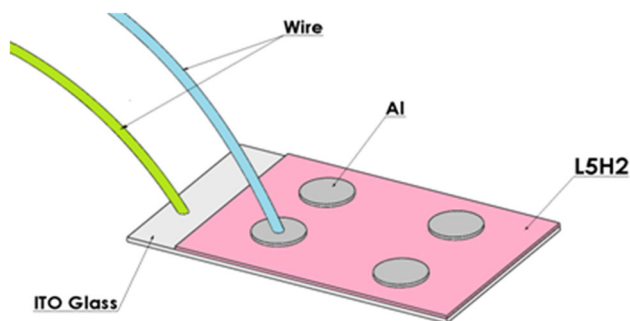
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In this work, the doped oligomer compound L5H2 is chosen for the fabrication of the Schottky diode due to its conjugated structure richness in 20-π-electron [31]. The plan of this investigation is to extract the parameters that control the device performance such as ideality factor, barrier height and series resistance from *I–V* device characteristics by using different methods at ambient temperature and moisture.

Sample preparation

L5H2 with molecular formula $C_{18}H_{12}N_4$ was used for the fabrication of Schottky diodes. The molecular structure of the L5H2 is shown in Fig. 1. The ITO glass substrate was cleaned for 1 min using acetone and after drying. The thin films of L5H2 were deposited by evaporation from a resistive heating element in a oil-pumped vacuum system with the chamber pressure at 5.2×10^{-5} torr on to the ITO glass substrates. The thin film layers were removed from the vacuum system and then doped by exposure to acetic acid vapour for 15 min. Finally, thermal vacuum depositions of aluminium metal contacts were produced using a shadow mask in the oil-pumped vacuum system. During thermal deposition the chamber pressure was 5.8×10^{-5} torr. The thickness of the electrode was approximately 100 nm and the thickness of L5H2 film was approximately 300 nm. A diagram of a Al/L5H2-doped surface-type Schottky diode device is shown in Fig. 2. The measurements were taken using current–voltage source keithley-230 Programmable Voltage and using keithley-485 Autoranging Picoammeter.

Results and discussion

The forward- and reverse-biased *I–V* and semi-log *I–V* characteristics of the Al/L5H2-doped surface Schottky barrier diode at ambient temperature and moisture are shown in Figs. 3 and 4. In forward bias, the Al contact was positively biased and the ITO glass was negatively biased. The *I–V* characteristics of the Al/L5H2-doped surface Schottky barrier diode showed rectification behaviour which is limited by the magnitude of the energy barrier at the junction interface. The rectification ratio was found to be 1.92 at ± 2.8 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

Fig. 1 Structure of L5H2

Fig. 2 The Schottky diode
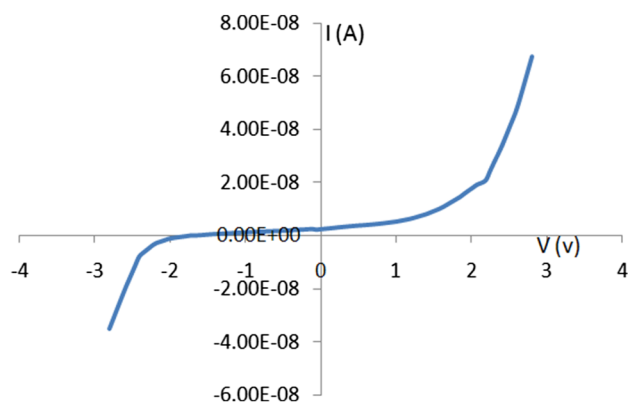
Fig. 3 The forward bias and the inverse bias *I* vs. *V* plot
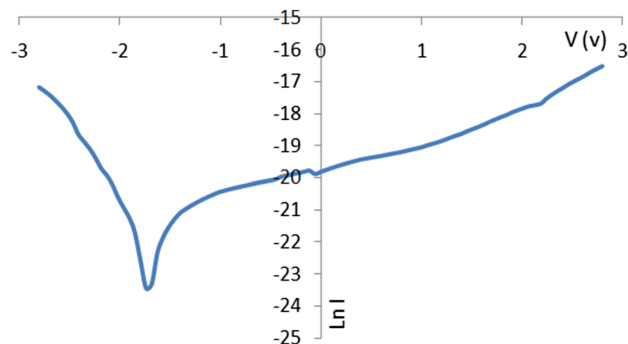
Fig. 4 Semi-log *I–V* curve of Al/L5H2-doped Schottky diode

theory, the current in Schottky barrier diodes can be expressed as [32].

$$I = I_0 \left(e^{\frac{qV}{nkT}} - 1 \right),$$ (1)

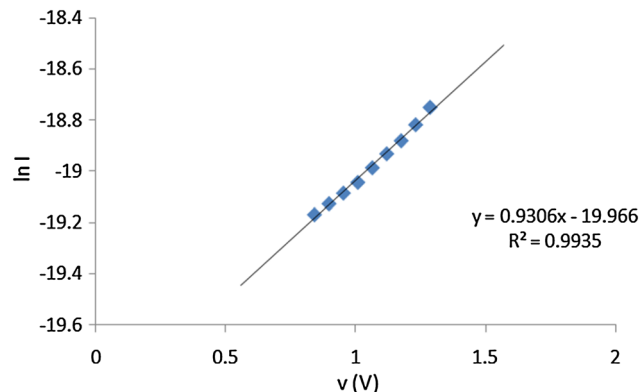where I_o is the reverse saturation current and can be expressed as

$$I_0 = AA^*T^2 e^{-\frac{q\varphi_b}{kT}},$$ (2)

where V is the applied voltage, A is the effective diode area (7.85×10^{-7} m^2), A^* is the effective Richardson constant (1.02×10^6 A/m^2 K^2, taken from Richardson's law), φ_b is the effective barrier height at zero bias, k is the Boltzmann constant (1.38×10^{-23} J/K or 8.62×10^{-5} eV/K). T is the temperature in Kelvin and n is the ideality factor. The value of ideality factor n can be calculated from the slope of the linear region of the forward bias Ln I–V plot using the following relation:

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

By using the above equation and slope of line in Ln I–V plot in Fig. 5, the value of ideality factor was calculated to be 42.9. The value of reverse saturation current obtained from forward bias semi-Ln I–V curve was 2.13×10^{-9} A.

For an ideal diode the value is unique. However, generally n has a value higher than unity. High values of ideality factor can be ascribed to the existence of local oxide layer on electrodes and non-homogenous barrier [23, 33] and [34]. Also, the high values of ideality factor may be attributed to other effects, for example organic layer effect, non-homogeneous thickness of organic film, etc. The value of zero bias barrier height was found to be 0.78 eV, which was calculated using Eq. (2). At low voltage, forward bias is linear in semi-log scale, but at higher voltages the device characteristics deviate from linear behaviour. It is well known that 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 [35]. If the affect of series resistance is more, then the nonlinear region of forward bias I–V curve will be large [36]. From the non linearity of semi-log I–V curve of Al/L5H2-doped Schottky diode at higher voltage, the value of series resistance was found to be 1.02×10^7 Ω. The graph of dV/d(ln I) vs. I is shown in Fig. 6. To find out the electronic parameter of the Schottky diode, the third method, which is known as Cheung and Cheung method, was used [37]. 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

$$I = I_0 e^{\frac{q(V - IR_S)}{nkT}},$$ (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 the functions and by using Eq. (4):
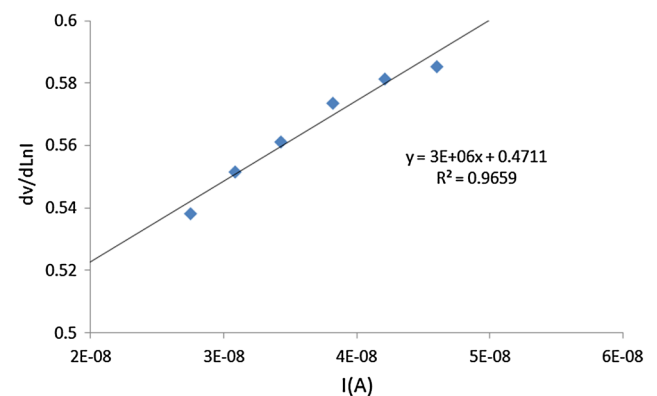
Fig. 6 The forward bias dV/(d(LnI) vs. I) plot of Al/L5H2-doped Schottky diode

Fig. 5 The forward bias Ln(I) vs. V plot of Al/L5H2-doped Schottky diode
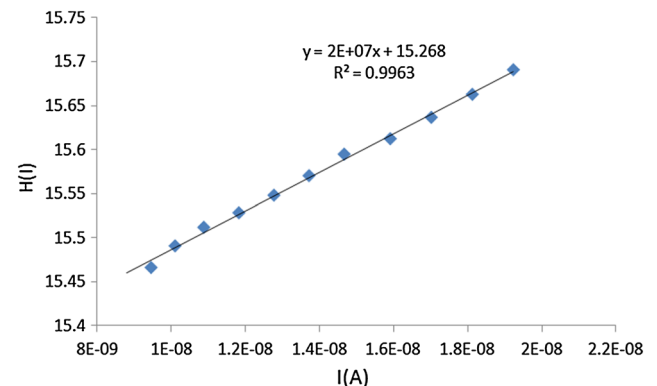
Fig. 7 The forward bias $H(I)$ vs. I plot of Al/L5H2-doped Schottky diode
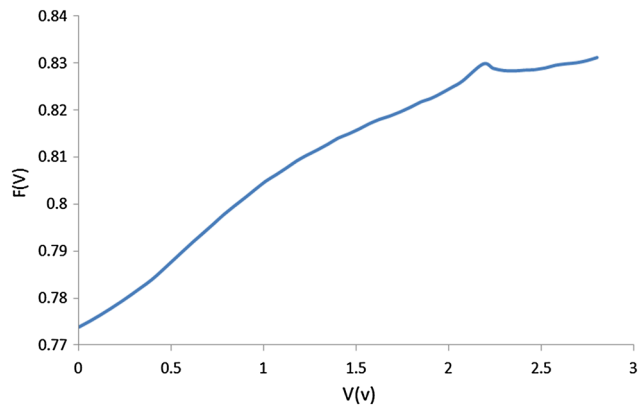
Fig. 8 The forward bias $F(V)$ vs. V plot of Al/L5H2-doped Schottky diode

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

The values of ideality factor and series resistance are obtained from the slope and y-axis intercept of the graph $dV/d(\ln I)$ vs. I.

And

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

$$H(I) = IR_s + n\varphi_b \qquad (7)$$

Also, the plot of $H(I)$ vs. I according to Eq. (7) gives a straight line with the y-axis intercept equal to $n\varphi_b$. The slope of this plot also gives the value of series resistance by which the consistency of Cheung's approach can be checked. The graph of $H(I)$ vs. I is shown in Fig. 7. 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 3×10^6 and $2 \times 10^7\ \Omega$, respectively. The average value of series resistance for the Schottky diode was found to be $1.15 \times 10^7\ \Omega$. As it can be seen, 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.

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 in 1978. The following equation has been used to express the modified Norde's method [38, 39]:

$$F(V) = \frac{V}{\gamma} - \frac{1}{\beta}\ln\left(\frac{I}{AA^*T2}\right) \qquad (8)$$

$$\beta = \frac{q}{kT}, \qquad (9)$$

where γ is a constant number ($\gamma \geq n$), n is the ideality factor and q is the electronic charge. It is shown that by plotting the function $F(V)$ a consistent value of the barrier height can be obtained even if there is a series resistance which would fetter the evaluation of the standard method. In this case, γ value is taken as 20.The plot of $F(V)$ vs. V has a maximum, if less than 20 are chosen, while the function should be a minimum only. The $I(V)$ is value of current taken from the I–VI–V curve. If the minimum of the $F(V)$ vs. V plot is found then the barrier height can be calculated using the following equation:

$$\varphi_b = F(V_{min}) + \frac{V_{min}}{\gamma} - \frac{1}{\beta} \qquad (10)$$

$F(V_{min})$ is the minimum value of $F(V)$, and $V_{min} = 2.61 \times 10^{-15}\ v$ is the corresponding voltage and it is close to zero. The Norde plot for Al/L5H2-doped surface-type Schottky diode is shown in Fig. 8. The value of the series resistance has been calculated from Norde's function for Al/L5H2-doped Schottky diode junction using the following relation:

$$R_s = \frac{\gamma - n}{\beta I_{min}}, \qquad (11)$$

where I_{min} is current in the minimum point of $F(V)$. Using Norde's method, the values of series resistance and barrier height were obtained as $1.2 \times 10^7\ \Omega$ and 0.75 eV, respectively. We can see from Table 1 the values of Schottky diode parameters obtained from the different methods. The barrier height and Series resistance show good agreement but not the ideality factors.

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

	Barrier height (eV)	Series resistance (Ω)	Ideality factor
Semi-log I–V	0.78	1.02×10^7	42.9
$dV/d(\ln I)$ vs. I plot	–	3×10^6	18.85
$H(I)$ vs. I plot	0.81	2×10^7	–
Norde's function	0.75	1.2×10^7	20

Conclusion

In conclusion, we have fabricated surface-type Al/L5H2-doped Schottky barrier diode. The electronic parameters such as ideality factor, series resistance and barrier height of the diode were determined by four methods. The majority of the parameters obtained using different methods are in good accord.

According to Table 1, barrier height is acquired minimum by Norde's function method (0.75 eV) and maximum by $H(I)$ vs. I plot method (0.81 eV), and series resistance is achieved minimum by $dV/d(\ln I)$ vs. I plot method (3 MΩ) and maximum by $H(I)$ vs. I plot method (20 MΩ). Also ideality factor is attained minimum by $dV/d(\ln I)$ vs. I plot method (18.85) and maximum by semi-log $I–V$ method (42.9). Then minimum values for series resistance and ideality factor is given by $dV/d(\ln I)$ vs. I plot method and maximum values for barrier height and series resistance by $H(I)$ vs. I plot method.

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