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Fabrication and Characterization of Al/Methyl Orange/n-Si Heterojunction Diode

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***Abstract*—**Herein, the organic semiconductor methyl orange (MO), is investigated for the first time for its electronic applications. For this purpose, Al/MO/n-Si heterojunction is fabricated through economical cheap and simple "drop casting" technique. The current-voltage (*I-V*) measurements of the device are made at room temperature under dark conditions. The *I-V* characteristics of Al/MO/n-Si junction exhibits asymmetrical and rectifying behavior that confirms the formation of diode. The diode parameters such as rectification ratio (RR), turn on voltage ($V_{turn\ on}$), reverse saturation current (I_0), ideality factor (n), barrier height (ϕ_b), series resistance (R_s) and shunt resistance (R_{sh}) are determined from *I-V* curves using Schottky equations. These values of these parameters are also extracted and verified by applying Cheung's functions. The conduction mechanisms are explained from the forward bias *I-V* characteristics using the power law.

***Keywords*—**Electrical properties, Organic/inorganic heterojunction diode, Methyl Orange, Cheungs Functions

I. INTRODUCTION

VERY recently, organic semiconducting materials have attracted great attention in the fabrication of rectifying diodes [1], [2] and many other devices such as organic sensors [3] organic photovoltaic devices [4], organic field effect transistor (OFETs) [5], [6] and organic light emitting diodes (OLEDs) [7]. This is mainly due to their advantages of low cost [8], tunability of electronic properties via chemical synthesis and ease of device fabrication. Also, organic semiconducting materials exhibit interesting electrical and optical properties [9]. In literature, some authors [10], [11] have reported the rectifying diodes by using small organic compounds that exhibited good stability as compared to polymeric materials. These materials have been demonstrated suitable for the fabrication of organic electronic devices [10], [12].

Among these small organic semiconductor molecules, Methyl orange (MO) is also a non-polymeric semiconducting material in the form of orange crystalline powder.

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The molecular weight and melting point of MO is 327.32 g/mol and ~300 ^{0}C, respectively. Primarily, MO is a pH indicator that is mostly used in chemical laboratories for indicating the pH. However, its chemical structure contains unsaturated bonds (i.e. richness in π-electrons) due to which it has the semiconducting properties. Moreover, the environmental stability and solution processability of MO made it one of the good candidates for the organic electronic applications. For this reason, MO is chosen for the fabrication of heterojunction device in this work.

In the present investigation, we have fabricated Al/MO/n-Si rectifying junction using MO as the active organic material by an inexpensive deposition method- drop casting technique. Various parameters of Al/MO/n-Si junction such as rectification ratio, barrier height, reverse saturation current, ideality factor, shunt and series resistances and conduction mechanisms were evaluated from *I-V* characteristics at room temperature in dark. This study confirms the application of MO in the field of organic electronics which we have investigated for the first time.

II. EXPERIMENTAL

In this work, commercially available organic semiconductor MO having molecular formula ($C_{14}H_{14}N_3NaO_3S$), purchased from ACROS, was used for the fabrication of the Al/MO/n-Si heterojunction diode. The molecular structure of MO is shown in Fig. 1. For the device fabrication, 3.0 wt. % solution of MO of was prepared in distilled water at 50 ^{0}C by using magnetic stirrer for five hours. For the film deposition, the prepared uniform solution of MO is drop casted on etched and cleaned n-silicon substrate. The MO/n-Si sample was kept to dry for 48 hrs at room temperature under nitrogen environment. When the MO film got dried, Aluminum (Al) electrode was thermally deposited on the top of MO film at 2.1×10^{-5} mbar using EDWARDS AUTO 306 Vacuum thermal evaporator system. The schematic diagram of the fabricated Al/MO/N-Si heterojunction is shown in Fig. 2.

The current-voltage (*I-V*) measurements were made on the Material Development Corporation (MDC) Probe station connected to a Keithley 237 voltage source/picoammeter.

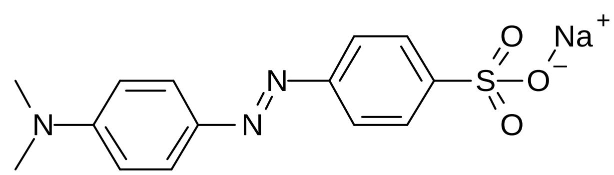

Fig. 1 Chemical structure of MO

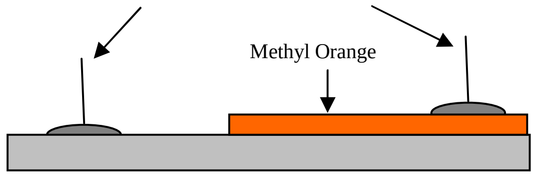

Fig. 2 Cross-sectional view of Al/MO/n-Si device

III. Results and Discussions

The *I-V* characteristics of Al/MO/n-Si are shown in the Fig. 3. The current in the device can be analyzed by using thermionic emission theory. According to this theory, the relation between current and voltage of the device can be expressed as [13],

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

Where I_o is the reverse saturation current and is expressed as follows [14],

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

and q is the electron charge, *V* is the applied voltage, A^* is the effective Richardson constant equal to 112 A/cm^2 K^2 for n-Si [15, 16], A is the effective diode area, T is the absolute temperature, k is the Boltzmann constant, n is the ideality factor and ϕ_b is the barrier height. The value of n is determined from the slope of the linear region of the forward bias semi log *I-V* characteristics through the relation [17],

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

The barrier height can be obtained from the following equation [18],

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

From Fig. 3, the turn on voltage $V_{turn\ on}$ is determined as 4.1 V, while the rectification ratio (RR), which is the ratio of forward current to reverse current at same voltage, is 6.12 at ±5.5 V.

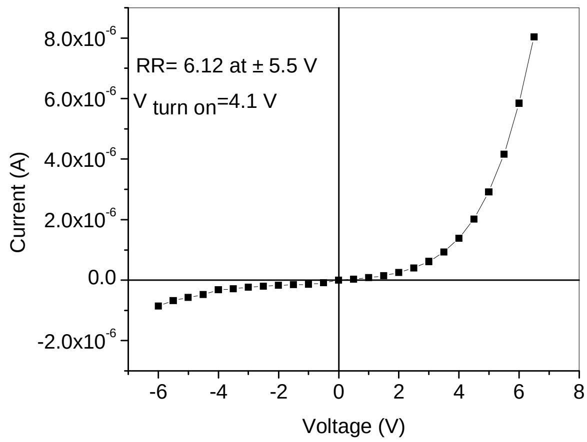

Fig. 3 Forward and reverse bias *I-V* curve for Al/MO/n-Si heterojunction diode

Fig. 4 shows semi logarithmic *I-V* curve of the device. The ideality factor "n" was calculated from the slope of linear region of the forward bias ln *I-V* curves and found to be 23 using equation 3. For ideal diode the ideality factor is unity but in this case the higher value of n may be due to the interface states, non-uniformity of the MO deposited film, series resistance or interfacial layer between the n-silicon and MO film. While the reverse saturation current I_0 is determined from the y-intercept of semi logarithmic curve and its value is 8.49×10^{-8} A. Applying (4) on Fig. 4, the value of ϕ_b is calculated which is 0.52 eV.

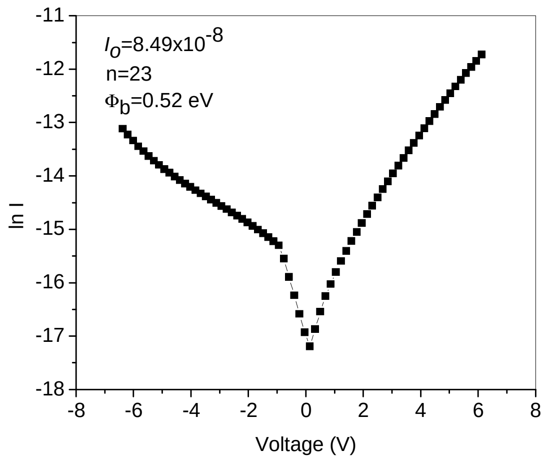

Fig. 4 Semi-log *I-V* characteristics of Al/MO/n-Si heterojunction diode

The series and shunt resistances of the Al/MO/n-Si heterojunction can be found by plotting the junction resistance against applied voltage as shown in Fig. 5. The values of series resistance R_s and shunt resistance R_{sh} are calculated as 449 kΩ and 15.3 MΩ, respectively.

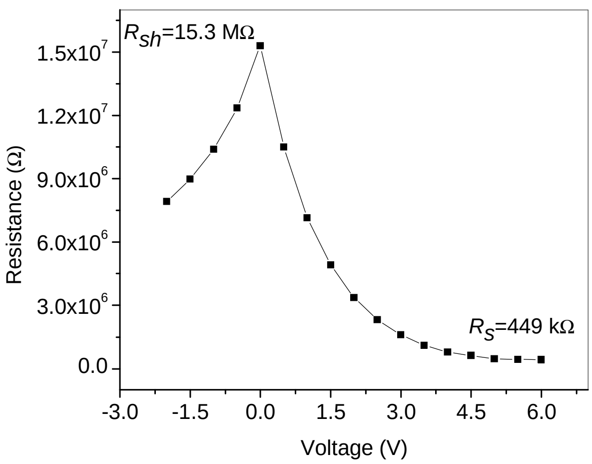

Fig. 5 Plot of the junction resistance between MO and n-Si heterojunction

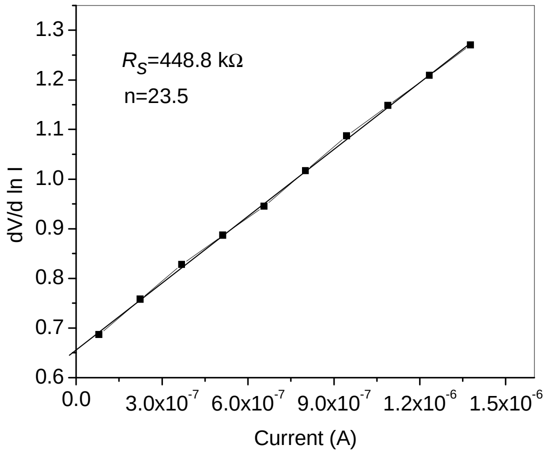

Fig. 6 d*V*/d ln*I* vs. *I* relationship of Al/MO/n-Si heterojunction

The values of the diode electronic parameters like n, R_s, and ϕ_b can be found by different methods. Here the values of these key parameters are verified by Cheung and Cheung functions [19]. Where the Cheung's functions are expressed as

$$\frac{dV}{d\ln I} = n\frac{KT}{q} + IR_s \tag{5}$$

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

and

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

The Plot of d*V*/d(ln*I*) vs *I*, shown in Fig. 6, is linear and gives R_s as the slope and nkT/q as the y-axis intercept. The values of n and R_s have been determined as 23.5 and 448.8 kΩ, respectively. From H (*I*)-*I* plot, shown in Fig. 7, the value of ϕ_b is calculated to be 0.56 eV. The values obtained by this method are in great agreement with the values determined by applying the thermionic emission theory to *I-V* characteristics.

The conduction mechanism through the junction can be studied by power law ($I \sim V^m$) from double logarithmic *I-V* curves, where different values of the m provide the information about the different mechanisms and its value is found from the slope of the linear regions of the double logarithmic curves.

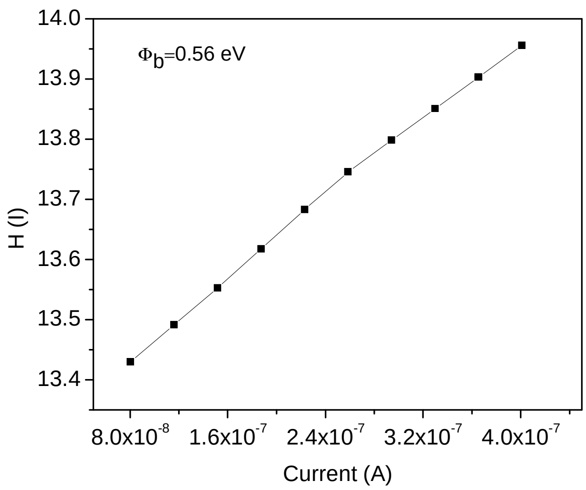

Fig. 7 *H*(I) vs. *I* relationship of Al/MO/n-Si heterojunction

The forward log*I*-log*V* characteristics shown in Fig. 8 consist of three distinct linear regions. The slope of region I is 1.3 which is close to unity so it defines the ohmic region, region II has slope of 2.2 which shows space charge limited current (SCLC) region and region III has slope 3.3 which represents trapped charge limiting current (TCLC) region.

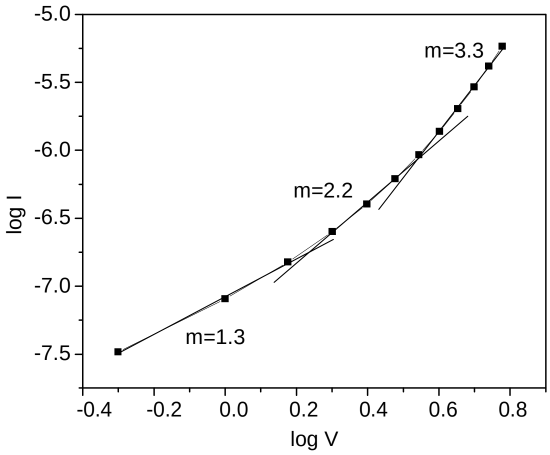

Fig. 8 log*I*-log*V* curve to explain the conduction mechanism in Al/MO/n-Si heterojunction diode

IV. Conclusion

This work reports the fabrication of Al/MO/n-Si heterojunction diode by a simple deposition technique i.e. the drop casting technique. The electrical properties of MO are investigated from *I-V* characteristics using thermionic emission model and Cheung's functions. The key diode parameters such as rectification ratio, turn on voltage, ideality factor, and barrier height are also extracted from *I-V* characteristics. The conduction mechanisms are investigated from *I-V* characteristics as well. It is concluded from this study that MO could be used alone or in combination with other organic semiconductor materials for the fabrication of organic electronic devices.

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