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Electrical Characteristics of Cadmium Sulfide/4-Amino-2-Methyl-Quinoline Heterojunction Structure

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Abstract

We fabricated a heterojunction structure composed of n-CdS and p-$C_{10}H_{10}N_2$ films. The CdS film was prepared using the CBD method, while the $C_{10}H_{10}N_2$ film was prepared using the spin coating method. Later, we performed the current-voltage (*I-V*) measurement of this PN diode which we made using Keithley 2400 sourcemeter. As can be seen from the *logI-V* diagram, this heterojunction structure exhibits rectifying properties. Using traditional methods, an ideality factor (n) of 1.93 and a barrier height value (Φ_b) of 0.79 eV were determined. An ideality factor of more than one indicates non-ideal *I-V* behavior in the CdS/$C_{10}H_{10}N_2$ heterojunction diode formed. The interface layer, interface states and series resistance are some of the causes of this deviation. Moreover, Cheung's functions and a modified Norde function were used to determine the diode parameters, such as ideality factor, barrier height, and series resistance. With the Cheung method, n=4.33, series resistance (R_S)=168.65 kΩ and Φ_b=0.62 eV were found. Additionally, R_S=686.08 kΩ and Φ_b=0.78 eV were found by the Norde method. Consistent barrier height values were found in all methods through comparison, suggesting compatibility. However, it was discovered that the series resistance values yielded by the Norde function exceeded those obtained by the Cheung functions.

Keywords: 4-Amino-2-Methylquinoline, $C_{10}H_{10}N_2$, CdS, Heterojunction Diode, Thin Film

1. Introduction

Currently, there is a growing interest in II-VI semiconductor materials due to their potential applications in the optoelectronic and photovoltaic industries. One particularly promising option is the thin film of cadmium sulfide (CdS), which is an n-type chalcogenide semiconductor with a direct energy band gap ranging from 2.28 eV to 2.45 eV. These thin films possess unique structural, optical, and electrical properties that differ greatly from those of bulk materials. As a result, they are used in various technologies, including solar cell window layers, optical sensors, transistors, diodes, and more. Different methods, such as electro-deposition, spray pyrolysis, successive ionic layer adsorption and reaction (SILAR), pulsed-laser deposition, vacuum evaporation, and chemical bath deposition (CBD), are employed to produce CdS thin films [1, 2].

A quinoline derivative, or 4-amino-2-methylquinoline (4-aminoquinaldine), is an organic compound with amine and methyl functional groups [3]. 4-amino-2-methylquinoline ($C_{10}H_{10}N_2$) is a quinoline derivative to have similar to structure such as naphthalene and 4-aminoquinoline [4]. Aminoquinolines are important as building blocks for the production of medicines and dyes, which are mostly used to prevent different illnesses [5, 6].

In this study, we used the CBD method to produce thin films of CdS. We then used the spin-coating technique to produce 4-amino-2-methylquinoline ($C_{10}H_{10}N_2$) films. A Keithley 2400 sourcemeter was used to record the electrical characteristics of the diodes in an atmospheric environment.

2. Materials and Methods

2.1. Materials and Synthesis methods

In this study, a Keithley 2400 sourcemeter was used to characterize the diodes electrically in an atmospheric setting. A thin layer of CdS was applied using the CBD method to a 76 x 26 x 1 mm³ indium tin oxide (ITO) substrate. The substrates were cleaned by rinsing them with ethanol and deionized water after being washed with a soap solution. After another rinse in deionized water, they were let to air dry. In order to deposit thin CdS films, a solution was made up of 8 mL of ammonia/ammonium chloride buffer solution (NH_3/NH_4Cl; pH=11.50), 1 M 10 mL thiourea ($CS(NH_2)_2$), and 0.2 M 10 mL cadmium acetate dihydrate ($Cd(CH_3COO)_2\ 2H_2O$). The mixture was then diluted with deionized water to reach a total volume of 50 ml. Thiourea was selected as the sulfur source (S), 82 °C was set as the solution temperature, and 60 minutes was the deposition time in order to prepare the CdS film [1, 2, 7]. After gathering in this manner, the CdS/ITO films were annealed for 30 minutes at 350 °C in room temperature.

CdS is categorized as an n-type semiconductor material [8], whereas $C_{10}H_{10}N_2$ behaves like a p-type semiconductor material, similar to 8-hydroxyquinoline (8HQ) [9], because they share functional groups. $C_{10}H_{10}N_2$ has an optical band gap energy of 3.5 eV [10].

It's time to finish the experiment's second step, which involves creating a diode by filming a $C_{10}H_{10}N_2$ layer on a CdS film. The $C_{10}H_{10}N_2$ film was prepared by dissolving powdered $C_{10}H_{10}N_2$ with a molecular weight of 158.20 g/mol in ethanol for 90 minutes at room temperature (22 °C). This solution was then used in the spin-coating process. There were 0.2 M of solution concentration and 30 mL of total solution volume. Using a plastic dropper, 10 drops of $C_{10}H_{10}N_2$ solution were applied to the CdS film prior to each rotation. The spin coater was attached to the CdS film that a $C_{10}H_{10}N_2$ solution was dropped onto. The spin coater was then turned on. The resulting film was allowed to stand at room temperature for five minutes after the spin coater was turned off after sixty seconds. The spin coater was restarted after five minutes, and the procedure was carried out eight times. The spin coater rotates at a speed of 1100 rpm for one minute during each rotation. As a result, a $C_{10}H_{10}N_2$ film was applied to the CdS film that had previously been prepared on ITO.

2.2. Electrical Characterization of the Heterojunction Structure

Using a Keithley 2400 sourcemeter, the electrical properties of the $CdS/C_{10}H_{10}N_2$ diodes were thoroughly characterized in this study.

3. Results and Discussion

As shown in Figure 1, electrical conductivity measurements were made on $CdS/C_{10}H_{10}N_2$ heterojunction structures using a two-point probe technique and a Keithley 2400 sourcemeter device. By using specialized computer software that was connected to the Keithley 2400 sourcemeter, current (*I*) values corresponding to applied voltage (*V*) were recorded. By applying a direct voltage (*V*) between -3 and 3 volts, the current (*I*) was obtained. Investigating the photosensitivity of the heterojunction diode we created was not the aim of this study. Because of this, *I-V* measurements were only carried out in the daytime at a temperature of 22 °C in a laboratory setting.

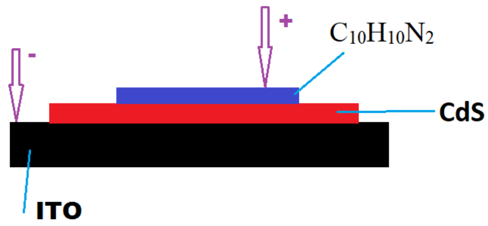

Figure 1. Measurement of electrical conductivity of $CdS/C_{10}H_{10}N_2$ heterojunction structure

Forward and reverse *I-V* measurements were made in the range of ± 3 V to ascertain the electrical properties of the sample; the corresponding graphics are displayed in Figures 2 and 3. These graphs demonstrate that the sample has a rectifying property and a potential barrier at the *I-V* interface.

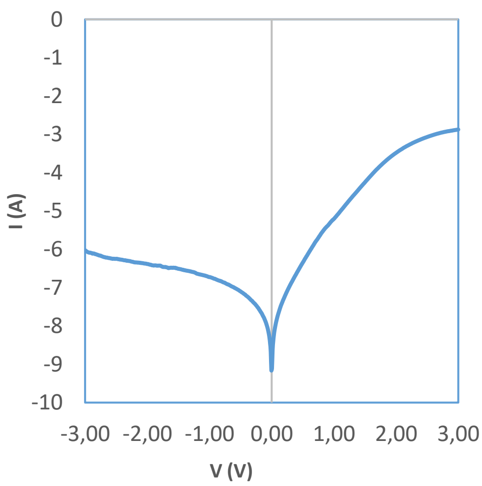

Figure 2. Semi-logarithmic reverse and forward bias I-V characteristics of $CdS/C_{10}H_{10}N_2$ heterojunction structure at room temperature

The unique current-voltage characteristic of the $CdS/C_{10}H_{10}N_2$ heterojunction diode is shown in Figure 2. When the voltage increases exponentially, the forward diode current also increases, indicating that the diode is rectifying. This suggests that a Schottky diode is analogous to how the heterojunction diode functions. The following formula 3.1 can be used to analyze the $CdS/C_{10}H_{10}N_2$ diode's current-voltage characteristics.

The electrical *I-V* characteristic of the n-CdS/4-amino-2-methylquinoline contact at room temperature was used in this study to obtain and compare diode parameters such as the ideality factor (n), barrier height (Φ_b), and series resistance value (R_S) of the structure. The Norde, Cheung Function, and conventional bias forward *I-V* approaches were applied for this. Similar to the R_S series resistance, the *Rsh* shunt resistance has also been calculated and published in a few places [11]. Here, we are only concerned with R_S's series resistance computation.

The relationship between the voltage applied to the contact and the current flowing through a Schottky barrier is given by Equation 3.1, which takes into account the series resistance (R_S) effect. This is expressed as follows:

$$I = I_0\left[exp\left(q\frac{(V-IR_S)}{nkT}-1\right)\right] \quad \textbf{(3.1)}$$

The ideality factor, denoted by n, has a value of 1 for an ideal diode. The value of 1 in parenthesis can be ignored in the equation if V>3kT/q. T is the ambient temperature in Kelvin, I_0 is the extrapolated saturation current value, and k is the Boltzmann constant in this expression.

Here,

$$I_0 = AA^*T^2\exp\left(-\frac{\Phi_{b0}}{kT}\right) \quad \textbf{(3.2)}$$

given in the form. q is the fundamental electric charge ($=1.6\times10^{-19}$ C), V applied voltage, A diode area (10.00×10^{-3} cm^2), A* effective Richardson constant for CdS is 45 Acm^{-2}K^{-2} [12].

Using Equation 3.1 to calculate the ideality factors of the diodes, the following expression can be obtained:

$$n = \frac{q}{kT}\frac{dV}{d(lnI)} \quad \textbf{(3.3)}$$

The value of the term $\frac{dV}{d(lnI)}$ in this expression is obtained by measuring the slope of the linear portion on the right-bias side of Figure 3's *lnI-V* graph.

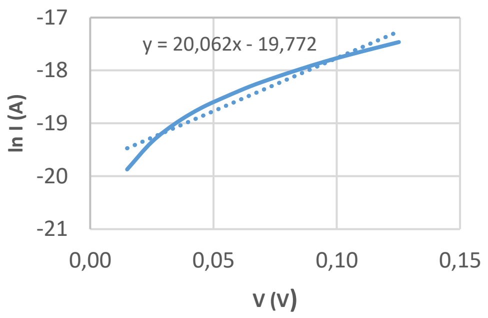

Figure 3. ln(I)-V characteristic of $CdS/C_{10}H_{10}N_2$ heterojunction diode in the range of 0.00 V- 0.13 V

The zero feed barrier height can be expressed as follows when equation 3.2 is rearranged:

$$\Phi_{b0} = \frac{kT}{q}ln\left(\frac{AA^*T^2}{I_0}\right) \quad \textbf{(3.4)}$$

As demonstrated in Figure 3, the *lnI-V* graph has been fitted linearly using the so-called traditional *I-V* method; diode parameters n, I_0 and Φ_{b0} are obtained with the aid of equations 3.2, 3.3, and 3.4. These parameters are 1.93, respectively; it was discovered to be 2.64×10^{-9} A and 0.79 eV. Table 1 lists the electrical characteristics that were acquired using conventional techniques.

Table 1. Electrical Characteristics Obtained by Traditional Methods

	n	I_0 (A)	Φ_b (eV)
I-V :	1.93	2.64×10^{-9}	0.79

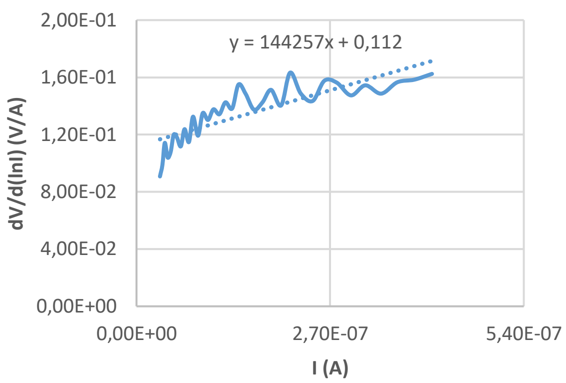

Figure 4. dV/d(lnI)-I graph of $CdS/C_{10}H_{10}N_2$ heterojunction diode at room temperature

In the literature, equations 3.5, 3.6, and 3.7 that are derived by taking into account the fundamental current equation 3.1 are referred to as Cheung functions [13]. In addition to R_S, values for n and Φ_b were also obtained using these equations.

$$\frac{dV}{d(lnI)} = IR_S + \frac{nkT}{q} \quad (3.5)$$

$$H(I) = V - \frac{nkT}{q}\ln\left(\frac{I}{AA^*T^2}\right) \quad (3.6)$$

$$H(I) = IR_S + n\Phi_b \quad (3.7)$$

Figure 4 displays the *dV/d(lnI)-I* graph of the sample's Cheung functions. Here, as Equation 3.5 makes abundantly evident, the line's slope indicates the value of R_S, and the point where the line crosses the vertical axis indicates the value of *nkT/q*. Thus, the diode's n value is 4.33, and the value of R_S was found to be 144.26 kΩ. Table 2 presents the electrical characteristics that were obtained using Cheung methods.

Table 2. Electrical Characteristics Obtained by Cheung Methods

	n	Rs (kΩ)	Φb (eV)
dV/dlnI-I :	4.33	144.26	
H(I)-I :		168.65	0.62

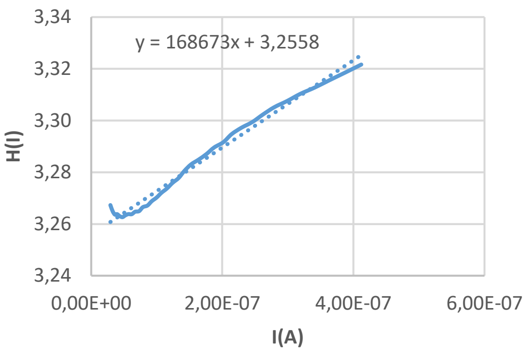

Figure 5. H(I)-I plot of $CdS/C_{10}H_{10}N_2$ heterojunction diode at room temperature

Figures 4 and 5 show an analysis of the Cheung function curves derived from the data in the nonlinear region of the $CdS/C_{10}H_{10}N_2$ Schottky diode's *I-V* curve. The diode's *H(I)-I* graph is drawn while taking Equation 3.6's Cheung function into account. Equation 3.7 was used to obtain Φ_b and R_S values after a linear fit was made to the *H(I)-I* graph shown in Figure 5. From this point on, the series resistance value was 168.65 kΩ and the barrier height value was 0.62 eV.

In addition, Norde put forth a different approach for figuring out the series resistance. The modified Norde method [14-16] defines the following function:

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q}\ln\left(\frac{I(V)}{AA^*T^2}\right) \quad (3.8)$$

In this case, γ stands for a dimensionless integer larger than the ideality factor (γ>n). According to this method, the barrier height and series resistance values can be obtained by applying the following relationships after locating the minimum point on the *F(V)* versus *V* plot:

$$\Phi_{b0} = F(V_0) + \frac{V_0}{\gamma} - \frac{kT}{q} \quad (3.9)$$

From the Norde functions, R_S value can be established as:

$$R_0 = \frac{kT(\gamma - n)}{qI_0} \quad (3.10)$$

Here, the corresponding bias voltage and current are indicated by V_0 and I_0, respectively, and the minimum point on the *F(V)* versus *V* plot is represented by $F(V_0)$.

Figure 6 shows the *F(V) -V* plot of the structure.

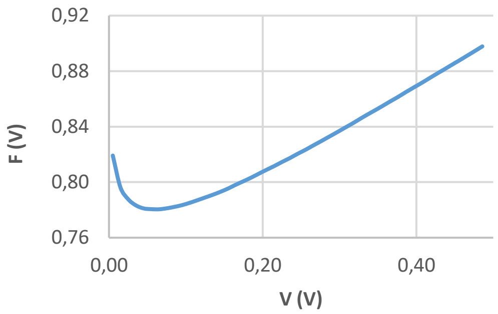

Figure 6. F(V)-V plot of $CdS/C_{10}H_{10}N_2$ heterojunction diode at room temperature.

Using Eq. (3.9) and (3.10), from the *F(V)–V plot*, the parameters of the structure were determined as Φ_b= 0.78 eV, R_S=686.08 kΩ by using $F(V_0)$ = 0.78 V, V_0= 0.06 V values. Electrical characteristics obtained by Norde methods are given in Table 3.

Table 3. Electrical Characteristics Obtained by Norde Methods

	Rs (kΩ)	Φb (eV)
F(V) -V :	686.08	0.78

Table 2 makes it evident that the Rs values derived from the *dV/dlnI-I* and *H(I)-I* lines were relatively near to one another. This shows that Cheung functions are compatible. A diode's series resistance can originate from various sources. The development of an insulating layer between the metal and semiconductor interface and the diodes' series resistance are particularly important factors that affect the performance and dependability of these diodes [17]. Several factors contribute to this, including the resistance of the semiconductor, the contact resistance of the metals deposited on it, the distribution of interface states, and the presence of an insulator between the semiconductor and the metal. The *dV/dlnI-I* graph in Table 2 yielded a value for n=4.33 that is higher than the value obtained using the conventional method. The Cheung functions take into account a different area of the *I-V* curve, which is one of the causes of this discrepancy. The data from the nonlinear region of the *I-V* characteristic is used by Cheung functions.

4. Conclusion

We have produced a $CdS/C_{10}H_{10}N_2$ heterojunction diode for our investigation. By using forward bias *I–V*, Cheung's functions, and Norde's functions, the electronic parameters of the Schottky diode, such as ideality factor, barrier height, and series resistance, were extracted. The series resistance values acquired using each method differ from one another, but they generally agree with the barrier height values.

At room temperature, it was discovered that the *I-V* characteristic of $CdS/C_{10}H_{10}N_2$ exhibited rectifying behavior, with an ideality factor value of 1.93 and a barrier height value of 0.79 eV. The n value is greater than one. This indicates that the diode is exhibiting non-ideal behavior. Among the factors contributing to this deviation are the interface layer, interface states, and series resistance. Moreover, the ideality factor, barrier height, and series resistance of the diode were ascertained using Cheung's functions and a modified Norde function. With the Cheung method, n=4.33, R_S=168.65 kΩ and Φ_b=0.62 eV were found. Additionally, R_S=686.08 kΩ and Φ_b=0.78 eV were found by the Norde method.

Comparison of all approaches revealed consistent barrier height values, indicating compatibility. The series resistance values produced by the Norde function, however, were found to be higher than those produced by the Cheung functions. With our study, we aimed to introduce the electrical properties of an organic compound, $C_{10}H_{10}N_2$, and an inorganic compound, CdS, as a diode, which has not been encountered previously in the literature.

Author's Contributions

Ramazan Demir: He produced and investigated the CdS film and heterojunction structure.

İsmet Kaya: He investigated some properties of the substance 4-amino-2-methylquinoline.

R. Demir and İ. Kaya revised the manuscript; and all authors read and approved the final manuscript.

Ethics

There are no ethical issues after the publication of this manuscript.

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