

## **Charge Transport Mechanisms and Device Parameters of CdS/CdTe Solar Cells Fabricated by Thermal Evaporation**

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*Abstract.* CdTe/CdS solar cells were fabricated entirely by thermal evaporation onto Indium-Tin-Oxide (ITO) coated glass substrates. The solar cells were characterized by I-V-T measurements conducted under dark and illuminated conditions. Dark characteristics show a diode like behavior with an ideality factor in the range of 3.1 and 4.9. This indicates that the current is dominated by recombination current in the junction region. This has been attributed to a large density of deep defects likely to be present in a highly mismatched (10%) heterojunction between CdTe and CdS. Power output and the fill factors of the cells have been calculated from the illuminated I-V characteristics which measure the short circuit currents and the open circuit voltages.

### **Introduction**

In the increasingly energy conscious world a great emphasis is being placed on developing alternate energy resources for sustainable development. The increasing reliance on fossil fuels like oil, gas and coal to power industrial development and improve the standard of living of the world population has created issues like global warming and pollution which threaten ecological balance and life itself on the planet.

Photovoltaic conversion of solar energy is one of the potentially viable and attractive options. It is clean, environmentally benign and available for free. This has prompted a continuous research effort for the last fifty years to develop

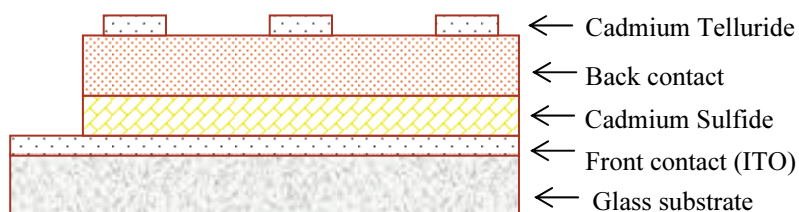
cheap and efficient solar cells. The major issues regarding a viable solar cell are the solar energy conversion efficiency, reliability and long term stability and most important of all economic viability. CdTe/CdS hetero-junction solar cell is a powerful candidate in this field. CdTe and CdS make an ideal pair for solar cell application. The as deposited n-type CdS with a band gap of 2.4eV is a suitable window material and permits a large part of solar spectrum to reach the absorber. On the other hand p-type CdTe having a direct band gap of 1.45eV is a near ideal absorber material<sup>[1]</sup>. Spectral output of the sun peaks at 1.43eV hence, CdTe is optimally matched to absorb maximum solar power. The fact that CdTe is a direct band gap material helps too, as it does not require much thickness of the material for the solar radiation to be absorbed completely. Most of the solar photons are absorbed in a thickness of 1-2  $\mu\text{m}$  from the interface with the window material<sup>[2]</sup>. CdTe/CdS solar cells currently hold a record of 16.5% energy conversion efficiency<sup>[3]</sup>.

This paper presents results of the study on the I-V-T characteristics both, dark and under illumination, of CdTe/CdS solar cells. These cells were fabricated entirely by thermal evaporation with a view to ascertain the current transport and loss mechanisms across the pn-junction.

### **Solar Cell Fabrication**

All CdTe/CdS thin film solar cells reported in this study were fabricated in the “superstrate” configuration. Superstrate configuration is referred to the solar cell structure where the solar radiation is admitted into the cell from the side of the substrate<sup>[4]</sup>. This implies that the window material (CdS in the present case) is deposited first followed by CdTe, the absorber material. Fig. 1 shows the geometry of the fabricated solar cells. They have the structure; (ITO coated glass substrate)/CdS layer/CdTe layer/(back-contact of Al). CdS/CdTe solar cells were fabricated by the process of thermal evaporation onto Indium tin oxide (ITO) coated glass substrates. Prior to the deposition of CdS and CdTe layers ITO coated substrates were thoroughly washed under running water and degreased by giving them a shake in an ultra sonic bath in ethyl alcohol. Samples were then subsequently dried under a hot air blower and were directly loaded into the vacuum coating unit. The first film to be evaporated was n-type CdS, which acts as the window. This was evaporated from a molybdenum boat. An Edward’s film thickness monitor FTM-7 was used to monitor the thickness of the films during evaporation. The thickness of this film was kept in the range between 250 and 500nm. This was followed by a second evaporation of a thicker layer of CdTe, which acted as the absorber. Both, CdS and CdTe were supplied by Alfa Aesar. Granules of CdTe having 99.99% purity were

evaporated from a tungsten boat. The thickness of the deposited layer was varied in the range of 0.5 to 4 microns.

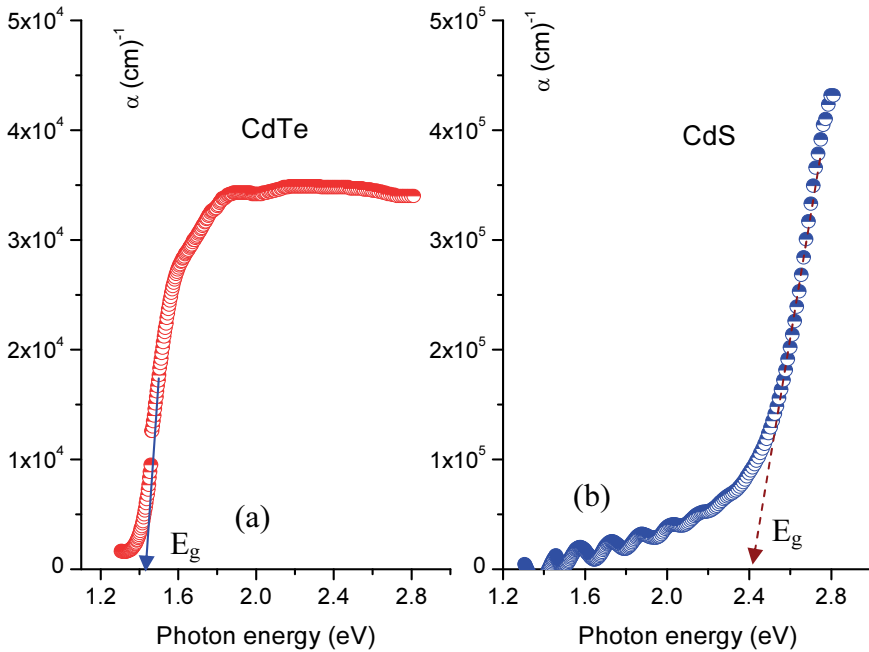


**Fig. 1. Structure of the ITO/CdS/CdTe/Metal Solar Cell.**

ITO/CdS/CdTe structures were annealed at an elevated temperature of 450°K for 15 minutes to enhance the grain size and increase the conductivity which results in enhanced fill factors. Following this treatment dots of Aluminum (Al) were evaporated as back contacts. These back contacts had a diameter of 4mm giving an active area of solar cells as ~12.6 sq mm.

### Optical Characterization of CdS and CdTe films

Before solar cells were fabricated using evaporated films of CdS and CdTe both types of films were evaluated for their band gaps as a means towards characterization. This was done optically by measuring the transmittance of the evaporated films<sup>[5]</sup> on a Perkin Elmer (Lambda EZ20) spectrophotometer. Absorption coefficient “ $\alpha$ ” was calculated using the methodology outlined by Lalitha *et al.*,<sup>[5]</sup>. Band gap of CdTe films was obtained by plotting “ $\alpha$ ” against “ $h\nu$ ” as shown in Fig. 2a. for a 500nm CdTe film. It can be observed that the extrapolation of the graph intercepts the photon energy axis at 1.45eV which is accepted value of the band gap for CdTe films<sup>[6]</sup>. Similar observations were made on the CdS films. The absorption coefficient for CdS film at different photon energies was calculated and plotted as shown in Fig. 2b. It is clearly observed that the band gap is 2.4eV which is the universally accepted value for the band gap of CdS<sup>[7]</sup>. It was therefore concluded that the process of evaporation yields good films of CdTe and CdS.



**Fig. 2.** The Absorption Coefficient Versus Photon Energy (a) for CdTe and (b) for CdS films.

### Electrical Characterization of CdS and CdTe Films

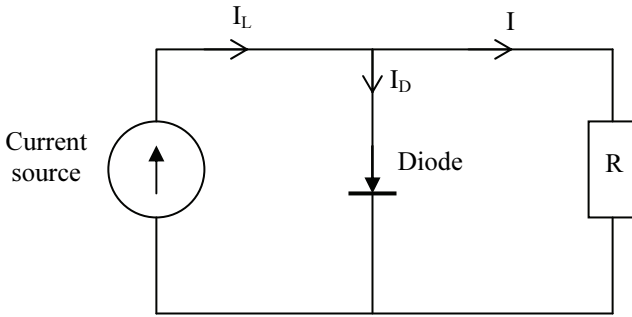
The fabricated solar cells were mounted inside an Oxford's Optistat DN-V vacuum cryostat. The temperature of the cryostat could be adjusted by an Oxford ITC-4 Temperature Controller. I-V-T characteristics were determined by using the Fluke 6306 automatic programmable RCL meter. A quartz iodine lamp from a slide projector was used as the light source as its spectral output closely resembles the solar spectrum. Full output of the quartz-iodine lamp of the slide projector was made to illuminate the solar cells. A water filter was placed between the light source and the solar cell to remove the infra-red radiation from the lamp to avoid any unnecessary heating of the cell. The results obtained are shown in the subsequent section. I-V-T measurements were used to determine the cell parameters like; the ideality factor 'n', the saturation current density 'I<sub>0</sub>' and the series resistance 'R<sub>s</sub>'. The information about the series resistance R<sub>s</sub> as a function of temperature is important as it deteriorates the fill factor FF of the device.

The current voltage (I-V) characteristics of the solar cell under illumination can be given as:

$$I = I_0[\exp(eV/nkT) - 1] - I_L \tag{1}$$

Here,  $I_L$  is the photocurrent,  $I_0$  is the reverse saturation current due to injection of holes and electrons across the junction,  $e$  is the electronic charge,  $k$  is the Boltzmann constant,  $n$  is the ideality factor and  $T$  is the temperature in degrees Kelvin.

The working of the circuit can be understood from the equivalent circuit diagram of the solar cell which is shown in Fig. 3.



**Fig. 3. Equivalent Circuit for An Ideal Solar Cell.**

Under illumination the solar cell is considered to be a current source driving a current through a load resistor “ $R_L$ ” which generates a voltage across the load resistor. Two extreme conditions can be envisaged<sup>[8]</sup>:

1. If the load resistance is zero (short circuit condition): The voltage across the load is zero ( $V = 0$ ) and a maximum current “ $I_{sc}$ ” called the short circuit current flows through the load resistor and the solar cell. Equation 1 reduces to;

2.

$$I_{SC} = I_L \tag{2}$$

3. For the load resistor to be infinity (Open circuit condition): A maximum voltage develops across the diode, which is called the open-circuit-voltage “ $V_{oc}$ ”. In this condition, no current flows in the circuit and the solar cell charges up to its maximum voltage which is equal to the built-in voltage of the cell.

$$V_{OC} = [nkT/q] \ln[(I_L/I_0) + 1] \tag{3}$$

Since power is  $I \times V$ , in either of the two conditions, the maximum power transferred to the load is zero.

### I-V-T Results of the CdTe/CdS Solar Cells

Temperature dependent current-voltage characteristics of the fabricated solar cells are shown in Fig. 4. The asymmetric nature of the characteristics is self evident. The behavior is the same as predicted for the pn-junction diode *i.e.* the forward current is higher than the reverse current. The nature of characteristics is indicative of a “soft diode”. Such diodes exhibit a gradual “turn-on” voltage for the forward direction and a continuous increase in current, rather than saturation, in the reverse direction. I-V-T data is further processed by plotting  $\log I_F$  against  $V_F$  (where  $I_F$  and  $V_F$  are the forward current and the forward applied bias respectively) which is shown in Fig. 5.

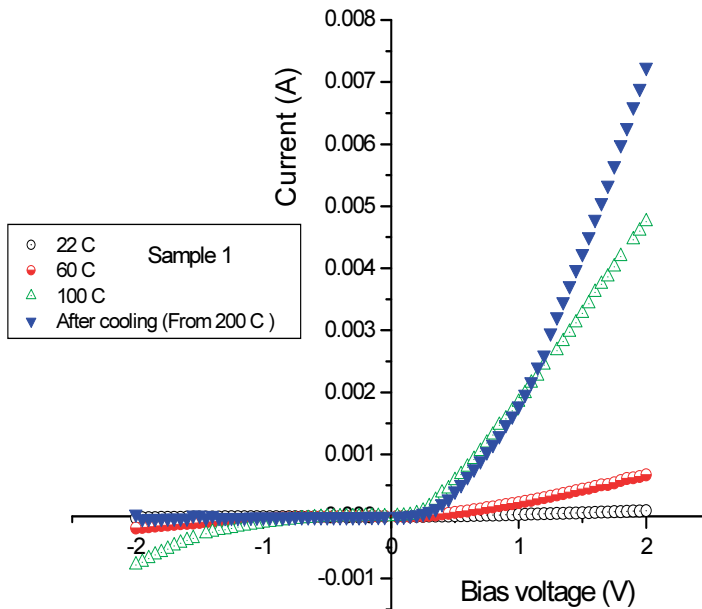


Fig. 4. I-V-T Behavior of a Typical CdS/CdTe Solar Cell.

Three important parameters can be determined from these plots.

(1) Using the diode equation;

$$I = I_0 \exp\left[\frac{qV}{nkT} - 1\right] \quad (4)$$

Since the factor 1 can be ignored for  $qV \gg nkT$ , the above equation reduces to:

$$I = I_0 \exp\left[\frac{qV}{nkT}\right] \quad (5)$$

The ideality factor “n” can be determined. It is an important figure of merit of a diode and is indicative of conduction processes in the pn junction region in addition to the ideal thermionic emission of carriers.

(2) Linear part of the log  $I_F$ - $V_F$  plot at higher bias voltages is also a straight line whose slope determines the series resistance “ $R_S$ ”. This is the resistance of the bulk of the diode after the pn junction has been “flattened” by the forward bias.

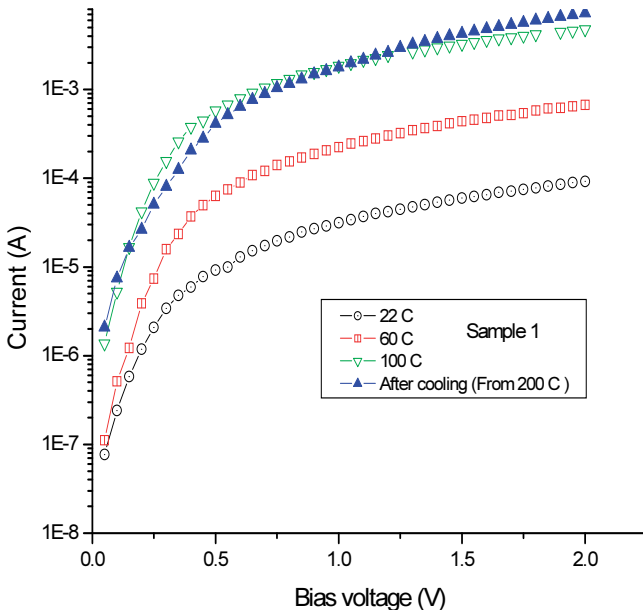


Fig. 5. Log  $I_F - V_F$  plots for CdS/CdTe Solar Cells.

(3) Intercepts of the plot with the current (y-) axis gives the value of the saturation current “ $I_0$ ” at any given temperature. Table 1 shows these quantities for three different temperatures for a typical solar cell.

Table 1. Various Parameters of a Representative CdS/CdTe Solar Cell.

Temperature (°C)	$I_0$ (A)	n	$R_S$ ( $\Omega$ )
22	$6 \times 10^{-10}$	4.9	20372
60	$2 \times 10^{-9}$	3.9	2760
100	$4 \times 10^{-9}$	3.1	385

The circuit shown in Fig. 6 is designed to vary the load across the solar cell. Changing the load resistor from very low (short circuit condition) to very high (open circuit condition), a graph as shown in Fig. 7 can be obtained under illumination.

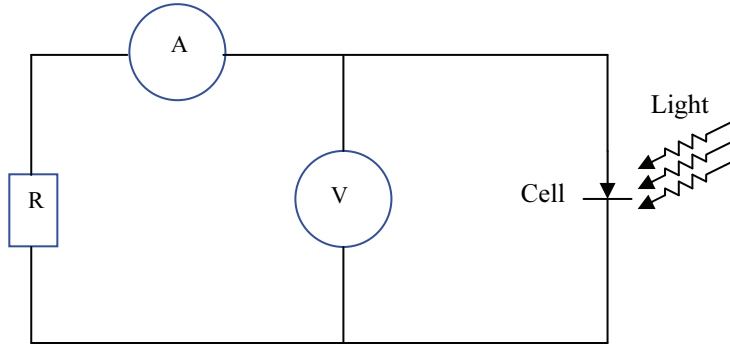


Fig. 6. Circuit to determine  $I_{SC}$  and  $V_{OC}$ .

For the given solar cell, the photo-induced current decreases from a maximum of  $30\mu A$  and near zero photo-voltage to less than  $3\mu A$  at  $280mV$ . The power dissipated in the load resistor is also shown plotted in the same figure. Power is found to peak at  $I_m = 18\mu A$  and  $V_m = 110mV$  giving a peak power output of nearly  $2\mu W$ . The efficiency of the power transfer capability of the solar cell is determined by the fill factor “FF” which is given by<sup>[9]</sup>:

$$FF = (V_m \times I_m) / (V_{OC} \times I_{SC}) \tag{6}$$

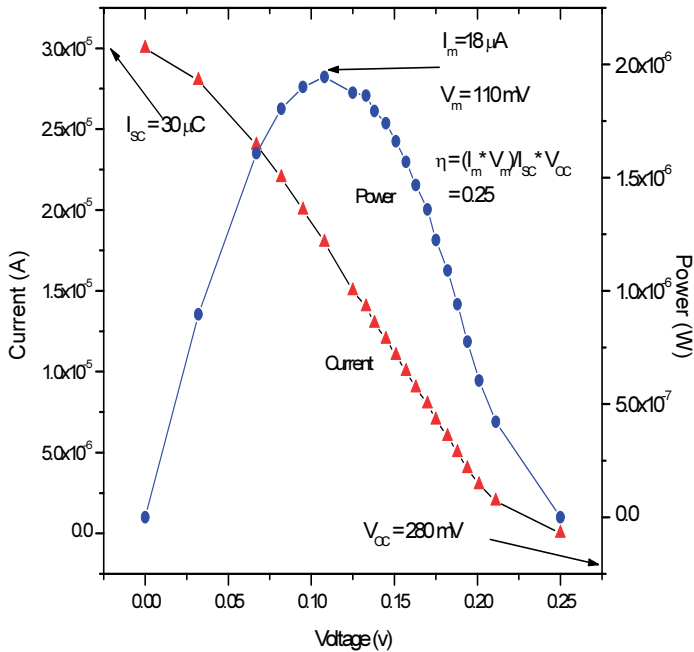


Fig. 7. Photo-current and Photo-voltage Characteristics of a Solar Cell.

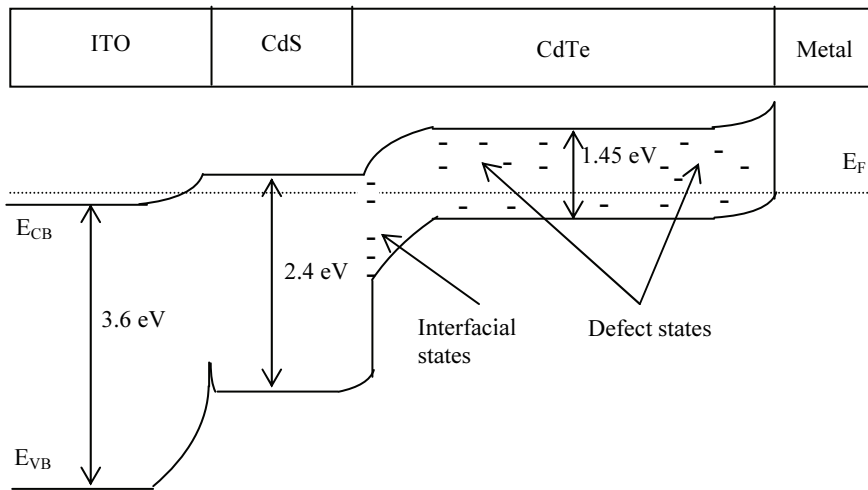


The fill factor FF also gives the efficiency “ $\eta$ ” of the power transferred by the solar cell to the load. It should be noted that this is not the efficiency of solar energy conversion by the solar cell rather it is a measure of the efficiency of transfer of converted energy to the load.

### Discussion

Current in an ideal pn-junction is carried by thermionic emission of carriers over the junction barrier<sup>[10]</sup>. Pure thermionic emission gives a value of near unity for the ideality constant ‘ $n$ ’. Any deviation in the value of ‘ $n$ ’ from unity is attributed to other current transport mechanisms like tunneling through the barriers and /or to the presence of a generation / recombination current in the junction region. In explaining the behavior of the ideality factor for the observed I-V characteristics, the existence of tunneling current can be safely discounted. Since neither the applied field was high enough nor the current temperature independent, which are specific properties of tunneling.

The possibility of a process of recombination of carriers in the depletion region is the most likely cause of the high values of the ideality factor. The cause for this is located in the structure of the photocell itself. Thin-film CdTe/CdS solar cells are essentially hetero-junction photodiodes. The band diagram of the CdTe/CdS solar cell is shown in Fig. 8.



**Fig. 8. Proposed energy band diagram of ITO/CdS/CdTe/Metal solar cell.**

The advantages of using CdS as the window layer and CdTe as the absorber layer have been outlined above. The two materials have different lattice constants and the hetero-junction suffers from a considerable lattice mismatch. The lattice mismatch between CdS and CdTe is 10%. The lattice constant for

CdTe is 6.48Å and for CdS it is 5.82Å giving a lattice mismatch of 10% [11], which is large enough to form recombination sites at the interface. This mismatch gives rise to interfacial defect states which tend to deteriorate the device performance by increasing the carrier recombination losses. However, it is significant to note that despite this handicap CdTe/CdS devices still perform reasonably well. To explain the relatively small impact of the defect states it has been suggested that the two material intermix at the interface during device fabrication and the transition from one material to the other is gradual thereby creating “a gradient in the film’s lattice constant” [12].

Lattice mismatch is not the only cause of defects in the films and at the hetero-interface. Disorder, which is present in thin films due to their amorphous nature, also causes defect states as do interstitials and other impurities. These defects are distributed in energy in the band gap and act as recombination centers. Deep defects, sometimes called mid-gap defects, are located near the middle of the band gap and usually act as recombination centers for electrons and holes. This causes a recombination current “ $I_R$ ”, in the direction opposite to the photocurrent as shown in Fig. 9.

Recombination current influences the fill factor “FF” most strongly. The shape of the bend in the I-V curve is influenced by the diode ideality factor “n”. For  $n = 1$  the current is thermionic in nature and the bend is sharp, almost a square. This gives a high value for  $I_m$  and  $V_m$ . For larger values of “n” the current in the pn-junction has components other than the thermionic like recombination via deep defect states and the I-V curve will be less than square and the corresponding values of  $I_m$  and  $V_m$  will be proportionally smaller. Increasing proportion of recombination via deep states will increase the value of “n” and reduce the fill factor. Fig. 10 shows the effect of annealing on the I-V characteristics. It is hypothesized that annealing results in reducing the strain at the junction and a reduction in the recombination current which improves the shape of the I-V characteristics. The greater curvature of the curve results in an improved fill factor. On the other hand the value of the ideality factor “n” improves as the temperature of the device is increased to 100°C increasing the thermionic component of the current.

The series resistance “ $R_s$ ” as seen in table 1 decreases rapidly from about 20 kΩ at 20 °C to 385 Ω AT 100 °C. This is seen as the resistance of the bulk of CdTe and CdS films in series with the contact resistances. The rapid drop in the value of resistance is attributed to the increase in conductivity of the semiconducting material, which increases exponentially with temperature. One of the causes for a poor fill factor is the high resistance at the back contact. It is extremely difficult to make an ohmic contact to a p-type material. It requires a metal with a high work function [13]. Several workers have suggested different regimes for making a low resistance (ohmic) contact to the p-type CdTe layer.

Optimum material and subsequent treatment for the back contact is yet to be found. However, it has been reported that the ohmic back contacts on CdTe requires a high work function material. Aluminum with a work function greater than 4.2eV is a possible choice.

## Conclusions

CdS/CdTe solar cells fabricated by thermal evaporation exhibit an open circuit voltage of around 380mV, which compares favorably with the reported values for similar structures. Thermionic current is the dominant mode of charge transport. However, due to the presence of a large number of defects present in the band gap of CdTe and at the CdS/CdTe interface generation recombination current influences the ideality factor. The high value of the ideality factor 'n' is attributed to the presence of these defects states which are present in amorphous/polycrystalline materials. The low value of the fill factor is due the series resistance of the thin window layer and the high resistance of the back contact.

## Acknowledgement

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## آلية نقل الشحنات ومعالم الجهاز للخلايا الشمسية المكونة من كبريتيد الكادميوم وكلوريد الكادميوم المحضرة بالتبخير الحراري

سعيد سالم بابكير

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جدة - المملكة العربية السعودية

المستخلص. لقد تم تحضير خلايا شمسية مكونة من كلوريد الكادميوم وكبريتيد الكادميوم (CdTe/CdS) بالتبخير الحراري على شرائح زجاجية مطلية بمركب الإنديوم وأكسيد القصدير (ITO). درست هذه الخلايا وميزت وذلك بقياس الجهد والتيار عند درجات حرارة مختلفة، تحت الإضاءة وفي الظلام. أظهرت قياسات الظلام مميز شبيه بالصمام الثنائي حيث عامل المثالية في حدود ٣,١ إلى ٤,٩، وهذا يدل على أن التيار يهيمن عليه تيار المعاودة في منطقة الوصلة. إن هذا يعزى إلى الكثافة العالية للشوائب العميقة المحتمل وجودها في وصلة عدم التجانس بين كلوريد الكادميوم وكبريتيد الكادميوم حيث يكون عدم التوائم عالياً (١٠%). قدرة الخرج وعامل الملء للخلايا تم حسابها من قياسات الجهد والتيار تحت الإضاءة حيث تم إيجاد تيارات الدوائر المغلقة وجهود الدوائر المفتوحة.