Study the efficiency of single crystal CdTe/ZnCdS solar cell at various temperatures and illumination levels

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ABSTRACT

CdTe is the best suited semiconductor for solar cells due to its band gap value 1.47 eV which is close to solar spectrum, low sublimation temperature and high absorption coefficient in the range of solar spectrum. To improve the photovoltaic performance of CdS/CdTe thin film solar cells, the CdS window layer is alloyed with different concentration of ZnS to reduce the resistivity and increase the band gap values. The single crystal CdTe based solar cell devices were prepared by vacuum evaporation method and have undergone for different temperature at various illumination levels to enhance the cell efficiency. We have achieved 14.37% efficiency and increased short circuit current density and open circuit voltage by reducing series resistance of the cell.

1. Introduction

Photovoltaic (PV) effect was discovered in 1839, but it remained of laboratory interest until the mid 1950s when US space program attempted to power satellite with PV cells. In 1954, single crystal silicon (sc-Si) PV cells of 6% efficiency were reported at Bell Laboratories. During the energy crisis of the early 1970s both public and private sector became interested in terrestrial applications of silicon based PV energy generation and gradually the research field shifted towards other PV materials like GaAs, InP, CdTe (Aurvtin et al., 2011) and CuInSe$_2$ based solar cells. During the past twenty years, these research and development efforts resulted in conversion efficiency improvements from 6% to 17% for CuInSe$_2$ based and from 8% to 16% for CdTe based, small area thin film modules for industrial level and the latest nanowires in window layer to improve the efficiency of cell (Fahrenbruch and Bube, 1983; Rommeo et al., 2010; Liu et al., 2011).

Here, we discuss the results of CdTe based single crystal solar cells where ZnCdS acts as window layer. Single-crystal substrates have been employed for the fabrication of heterojunction photovoltaic devices. In the heterojunction photovoltaic devices n-type window layer is deposited on any suitable p-type single-crystal substrate. Now a lot of research is being carried out with various combination of materials used for PV devices. The single crystal substrate has been used for the fabrication of heterojunction photovoltaic devices of the type n-CdS / p-InP, p-CdTe, p-GaAs or p-Ge. Analysis of the photovoltaic response shows that all the devices generally have good collection efficiency (Arienzo and Loferski, 1980). Cells using single crystal CdTe have been reported with solar efficiencies as high as 12% (Yamaguchi et al., 1977).

2. Fabrication of PV devices

The standard preparation of single crystal p-type CdTe, consists of lapping the substrates and then polishing with 1-μm alumina, followed by cleaning in organic solvents and etching in a 5% bromine-in-methanol solution (Br$_2$:MeOH) for a few minutes. A final etching step in Br$_2$:MeOH is always preformed to achieve a shiny and residue-free surface prior to any further surface treatment or window material deposition. Polishing and subsequently etching surfaces of various orientations provide the primary source for CdTe samples (Werthen et al., 1983). The single crystal CdTe samples are subsequently ready to be used as p-type absorber layer for any material like CdS/ZnCdS as window layer.

After cleaning the single crystal p-CdTe which is commercially available with dimension 10 ∗ 10 ∗ 0.5 mm, n-type ZnCdS layer is grown on the top surface, which serves the function of window layer. It may be deposited by a number of techniques like vacuum evaporation, close space sublimation, chemical vapor deposition or

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radio frequency sputtering. In the present work vacuum evaporation technique was used. $Zn_xCd_{1-x}S$ compositions were prepared by mixing CdS and ZnS powder (Merck-99.99% pure) with ratios $x = 0$ to $x = 1$, where x is the ratio of the zinc. Then we developed $Zn_xCd_{1-x}S$ thin films of different compositions in vacuum evaporation plant by using Edward's coating unit which proved to be good as widow layer (Zia et al., 2010). The evaporation conditions were used during present investigations were nearly same for all compositions. The source current and chamber pressure were kept to be 50–65 amperes and batter than 10^{-5} Torr respectively. The deposition rate was 0.4 nm per second, while the substrates remained at room temperature. The deposited films were nearly 0.3 μm thick and stable under air atmospheric condition.

The formation of an ohmic contact between a p-type semiconductor and a metal can only be obtained when the hole affinity in the semiconductor, χ_h, is lower than the work function of the metal, $\char{c}_m$. Otherwise a potential barrier for holes (Schottky barrier) at the interface results in a high contact resistance. Unfortunately, there are no metals with a work function higher than the hole affinity of CdTe, $\chi_h = 5.78$ eV (Swank, 1967; Gessert, 1996).

Another approach for achieving good back contact is based on depositing a heavily doped p-type semiconductor interlayer with a high work function (like ZnTe) on top of CdTe before metallization. The small valance band offset between ZnTe and CdTe (0–0.2 eV) (Riovx et al., 1993; Aven and Segall, 1963) leads to a low potential barrier at the interface and hence an easy hole transport between layers. ZnTe thin films of few nanometers were prepared by electron beam evaporation technique. During the deposition of these films the base pressure is less than 10^{-5} torr while high tension current and voltage were kept nearly at 12 mA and 2 kV respectively.

Finally ZnCdS/CdTe/ZnTe single structure is pasted on conducting silver painted copper strip which acts as back contact. The front contact is made at the window layer of ZnCdS thin film by applying silver conducting paint at the points of contact.

2.1. I–V characteristics measurement

Solar cells were characterized by current–voltage (I–V) relation in dark and under illumination. Current–voltage measurements, under illumination, were performed at various temperatures i.e, from 280 to 320 K by using Solar Simulator of type Photo Physics with 2 atmospheric mass which is normalized to 100 mW cm^{-2}. Different illumination levels in this study were represented as 1, 2, 3, 4 and 5 means 100, 52, 27.8, 12.8 and 4.1 mW cm^{-2} respectively. I–V characteristics of a cell are measured with a home made temperature controlled unit using Peltier effect. This system consists of stainless steel chamber to hold the sample, K-type thermocouple, coolant body and solar simulator.

The associated facility is composed of a power supply and a source meter from where we supply voltage to the sample and get the current after passing through the cell. The voltage varies in steps of 0.1 V and corresponding current can be measured by source meter. All the measurements are performed automatically at different temperature by varying incident light from solar simulator. From this data we can plot the I–V curves and measure the fundamental cell parameters (V_{oc}, J_{sc}, J_m, V_m, ff, R_s, R_{sh}, η).

The internal and external parameters of a solar cell are usually evaluated from the experimental J–V curves. The J–V characteristics of an ideal cell with a single dominant current transport mechanism can be represented by an expression such as

$$J = J_o[\exp(qV/AkT) - 1] - J_L \tag{1}$$

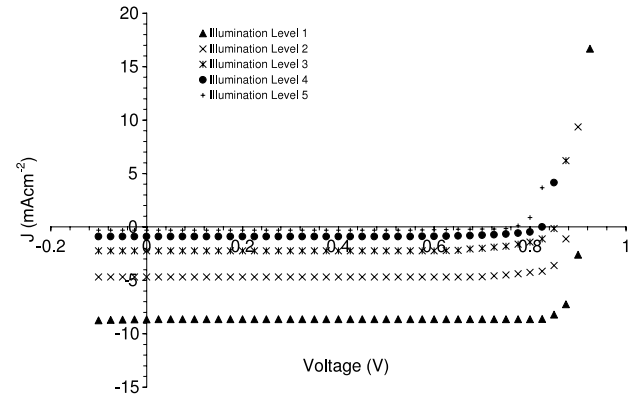at least over the range of J values that determine the solar efficiency.

Fig. 1. J–V plots of single crystal CdTe based solar cells at 290 K for various illumination levels.

Although the fundamental parameters of the solar cell are J_L, J_o, A, and R_S, the usual description is in terms of V_{oc}, J_{sc}, and ff. These parameters are useful, intuitive, and easily measured.

Ideal solar cell, derivation of relations among solar efficiency η, J_o and A shows that how solar efficiency η is affected by parallel and series resistances. Using global computer numerical solution, the dependence of J_o and A on illumination intensity and the variation of η with temperature and illumination level is also discussed (Fahrenbruch and Bube, 1983).

The standard measurements of current versus voltage, under illumination, enable one to obtain values for the principal parameters defining solar cell performance which include short circuit current density J_{sc}, open-circuit voltage V_{oc}, fill factor ff, and solar efficiency η. These measurements may be repeated as a function of temperature.

The Shockley diode model (Schokley, 1949) is used to find out the cell's internal parameters, i.e., shunt and series resistances, R_s and R_{sh}, reverse saturation current J_o, ideality factor A, and the light generated current density, J_L. These values are calculated from the I–V data under illumination. However, the J_o and A values were also obtained from the dark data.

3. Results and discussion

The values of J_{sc}, V_{oc}, ff, and η are measured, from the J–V plots at various temperatures for various illumination levels as given in Fig. 1. It is found that J_{sc}, V_{oc}, ff, and η increase as the light intensity increases as shown in Figs. 2–5. It is physically insightful to treat the variation of η with intensity by separate consideration of J_{sc}, V_{oc}, and ff. It is found that the effect of series resistance on ff is usually more crucial than the rise in cell temperature due to high illumination levels. The fill factor increases slowly with intensity for zero R_s. The light generated current density ($J_L \approx J_{sc}$) is proportional to photon flux Γ as long as the minority carrier lifetime in the absorber is constant. At higher photon fluxes however, increased carrier traffic begins to saturate the recombination centers, increasing the lifetime and thus producing an increase in quantum efficiency (Vasil'ev et al., 1975).

The open-circuit voltage increases with intensity as $\ln[J_L(\Gamma)/J_o]$ until, at high injection levels, more complex effects come into play. These effects include the voltage drop across the depletion layer at the junction, which becomes appreciable at high V_{oc}, and a change from $A \sim 1$ transport to high injection, $A \sim 2$ transport.

Results of internal PV parameters R_s, J_L, A, and J_o were also calculated and found that the values of shunt resistance R_{sh}, measured at various temperatures and illumination levels are infinity in our calculations as given in Table 1. The reason for this observation is that usually two points are used in these calculations. The light generated current density J_L decreases exponentially as we decrease the

Table 1
External PV parameters at 290 K ($\pm 5\%$).

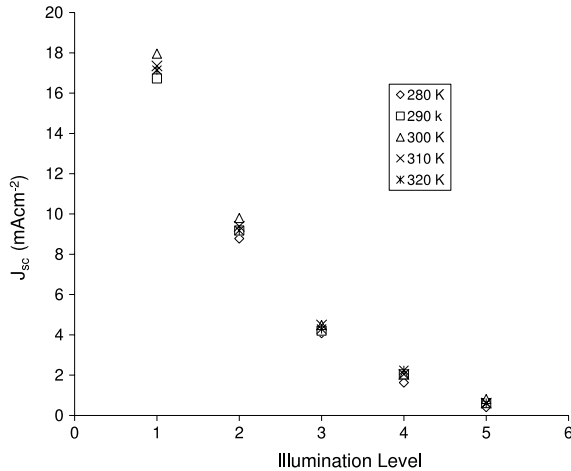| Sr. No	Illumination level	J_{sc} mA cm^{-2}	V_{oc} mV	FF %	η %
1	1	17.96	920	86.97	14.37
2	2	9.8	880	79.58	13.19
3	3	4.49	841	67.26	9.14
4	4	2.04	820	59.07	7.72
5	5	0.816	780	23.88	3.7

Fig. 2. J_{sc} versus illumination level at various temperatures.
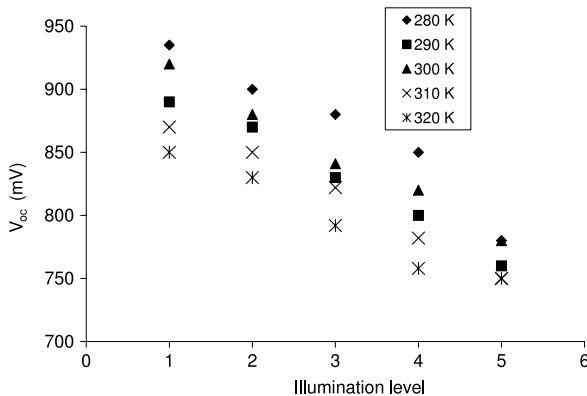

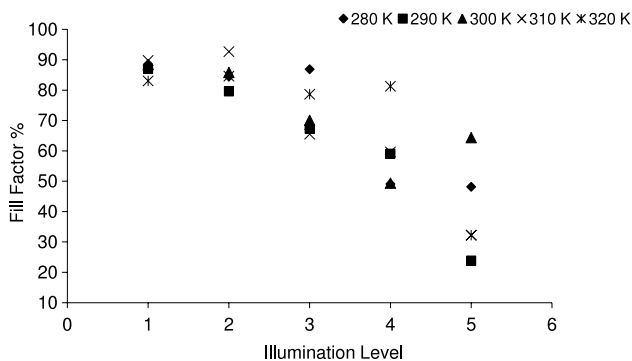**Fig. 3.** V_{sc} versus illumination level at various temperatures.

Fig. 4. Fill factor (ff) versus illumination level at various temperatures.

Fig. 5. Efficiency (η) % versus illumination level at various temperatures.

some of the heterojunction cells show a variation of the diode J_o and A factor with illumination level. This is particularly true when trapping centers are not in good thermal communication with conduction or valence bands and can have their occupancy, and hence charge, changed by illumination.

The effect of temperature on A and reverse saturation current density J_o shows that as we increase the temperature the values of A and J_o decrease. The value of J_o decreases exponentially with increasing temperature due to changes in n_i. The variation of minority carrier lifetime t with temperature is complex. It depends on many factors like the position and location of recombination–generation centers in the band gap, their capture cross sections for electrons and holes, the working temperature and the position of quasi Fermi levels under non-equilibrium condition. The strong temperature dependence of n_i causes T to increase almost exponentially with temperature.

Solar efficiency η increases almost logarithmically with increasing intensity until high injection and series resistance effects cause it to saturate or even decrease with increasing concentration. Previously reported results by Matsune et al. (2006) produced CdS/CdTe based solar cell and show that efficiency η = 15%, with J_{sc} = 25.5 mA cm^{-2}, V_{oc} = 0.82 V, ff = 0.72. Gupta et al. (2006) report an efficiency of 8% for CdTe based solar cell with V_{oc} = 0.755 V, ff = 0.61. Calixto et al. produced (Calixto et al., 2007) CdS/CdTe based solar cell by CBD method which shows efficiency η = 12.34% with V_{oc} = 0.74 V, J_{sc} = 23.8 mA cm^{-2}, ff = 0.705. Hadrich et al. (2007) produced CdS/CdTe based solar cell which shows efficiency $_s$ = 8.2% with V_{oc} = 0.68 V, J_{sc} = 21.3 mA cm^{-2}, and ff = 0.57. Seymour (2005) produced CdTe based solar cells treated with Cu, having an efficiency $_s$ = 12.4% with V_{oc} = 0.82 V, J_{sc} = 23.9 mA cm^{-2} and ff = 0.63 and Jvdith (Schaffner et al., 2011) shows efficiency 12% by using copper in CdTe. Razkov also shows the latest evaluation of the conversion efficiencies of various type of research PV Cells (Razkov et al., 2011). The effect of temperature on the cell's parameters, obtained in the range of 280–320 K, at various illumination levels. η, V_{oc}, J_{sc} and ff are also found to be nearly constant.

4. Conclusion

CdTe based solar cells of high efficiency up to 14.37% (with $\pm 5\%$ standard error) have been developed at 290 K with illumination of

illumination level. Decrease in J_L may be due to increase in series resistance, when we decrease illumination intensity the series resistance R_s increases exponentially, which is opposite behavior as shown by J_L.

The values of ideality factor A and reverse saturation current density J_o slightly change by changing illumination level because
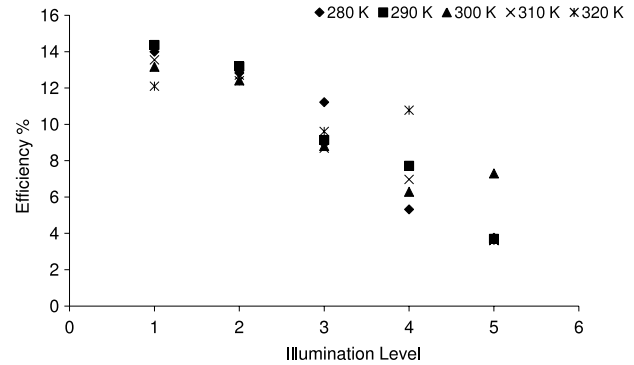
100 mW cm^{-2} where V_{oc} = 920 mV, J_{sc} = 17.96 mA cm^{-2} and fill factor is 87%; with a simple vacuum co-evaporation technique. It is seen that the efficiency of the cell is directly illumination dependent. To improve the performance of window layer, we have used zinc as a dopant in CdS which reduced the resistivity of window layer and increases the current density. In order to reduce the recombination ratio it is necessary to improve the back contact performance, we have developed ZnTe thin film between CdTe and back contact. During this study we have obtained the best efficiency of the solar cell at the temperature 290 K while illumination level is 100 mW cm^{-2}.

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