CHAPTER – V  I-V CHARACTERISTICS OF Glass/TCO/CdS/CdTe/Au HETEROSTRUCTURE SOLAR CELLS

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CHAPTER – V

I-V CHARACTERISTICS OF Glass/TCO/CdS/CdTe/Au HETEROSTRUCTURE SOLAR CELLS

5.1 Introduction

Now-a-days, cadmium telluride (CdTe) has been considered as one of the most promising semiconducting absorber thin films for large area thin film solar cells with low production cost. CdTe has an energy gap of 1.45 eV, very well suited for absorbing the solar light spectrum. The energy gap is “direct,” resulting in high absorption coefficient for visible light of $> 10^5 \text{ cm}^{-1}$ so that the absorber layer needs only a few $\mu\text{m}$ thick to absorb $> 90\%$ of light above the band gap [1]. Moreover, the constituting elements have a significantly higher vapor pressure than the compound. In the high temperature phase, a slight non-stoichiometry is present in the form of a slight Cd deficiency. This perturbation, probably in the form of Cd vacancies, leads to a native $p$-doping of films. This is fortunate, in that when the absorber, in our case CdTe, is $p$-type, electrons with their high mobility are the photo-generated minority carriers. This property makes it relatively easy to produce CdTe films suited for thin film solar cells. The only requirement is absence of disturbing impurities, which might jeopardize the doping. Besides, it possess strong ionicity of 72% [2], the energy of any photon in the solar spectrum is lower than the energy of the chemical bonds ($> 5 \text{ eV}$) in CdTe or CdS. The strong bonding leads to an extremely high chemical and thermal stability, reducing the risk of degradation of performance of any liberation of Cd to a very low level.

Among the polycrystalline heterojunction solar cells, the $p$-CdTe/$n$-CdS heterostructure has become one of the most promising candidates for use in low cost, large-scale photovoltaic device applications owing to its high absorption, optimum energy band gap, and the ease of thin film preparation by a variety of techniques. The details of CdS/CdTe solar cells have been
discussed elaborately in chapter I along with the review on the literatures of said heterojunction photovoltaic device.

The pure and Cu doped (2 wt.%, 3 wt.%, 4 wt.%) CdTe thin films have been deposited on transparent conducting oxide (TCO) substrate, (i.e. fluorine doped tin oxide (SnO$_2$:F or FTO) coated glass substrate) at RT, 100, 150 and 200°C using electron beam evaporation technique. In addition, the p-n heterostructure, Glass/TCO/n-CdS/p-CdTe was also prepared by the electron beam evaporation technique at RT, 100, 150 and 200°C, to study its photovoltaic performance. From the observations of the films deposited on glass substrate (discussed in chapters III and IV), it is confirmed that the optimum annealing temperature for the better physical properties is 400°C. Hence, the above said samples were annealed at 400°C. In this chapter, the results on the structural, optical, and photoluminescence properties of CdTe, CdTe:Cu, CdS/CdTe, and CdS/CdTe:Cu films deposited on the TCO substrate have been discussed. Further, the photovoltaic performance of Glass/TCO/CdS/CdTe/Au solar cells have been studied by the effects of dopant (Cu) concentration and substrate temperature and the results are presented elaborately.

5.2 Solar cell: introduction

The temperature difference between the surface of the sun (T = 5800 K) and the surface of the earth (T = 300 K) is the driving force of any solar energy conversion. Solar cells and solar modules directly convert the solar light into electricity using the internal photoelectric effect. Thus any solar cell needs a photovoltaic absorber material that is not only able to absorb the incoming light efficiently but also to create mobile charge carriers, electrons and holes, that are separated at the terminals of the device without significant loss of energy. In organic absorber materials, most light-absorption processes generate excitons and a first step of charge separation
is necessary in order to dissociate the exciton into free carriers. In contrast, the low binding energy of excitons in inorganic semiconductors makes absorption and generation of mobile charge carriers virtually identical in appropriate absorber materials of this type. Thus, after light absorption electrons and holes are present in the absorber and must be directed towards the two different contacts to the absorber, that is, the final charge carrier separation step.

For a photovoltaic absorber material, its band-gap $E_g$ is the primary quantity defining how many charge carriers are generated from solar photons with energy $E > E_g$. Maximizing the number of photons contributing to the short-circuit current of a solar cell would require minimizing $E_g$. Since photogenerated electron hole pairs thermalized to the conduction band and valence band edges after light absorption, the generated energy per absorbed photon corresponds to $E_g$ regardless of the initial photon energy $E$. Thus, maximizing the band gap energy $E_g$ maximizes the available energy per absorbed photon. Therefore one intuitively expects that an optimum band gap energy exists between $E_g = 0$, maximizing the generated electron-hole pairs, and $E_g \rightarrow \infty$, maximizing the generated energy contained in a single electron-hole pair. Quantitatively, this consideration is reflected in the dependence of the maximum achievable conversion efficiency of a single band-gap photovoltaic absorber material [3].

The maximum power conversion efficiency of a solar cell consisting of single semiconducting absorber material with band-gap energy ($E_g$) is described by the Schokley-Queisser (SQ) limit. SQ limit relies on four basic assumptions [4]:

1) The probability for the absorption of solar light by the generation of a single electron-hole pair in the photovoltaic absorber material is unity for all photon energies $E \geq E_g$ and zero for $E < E_g$.

2) All photogenerated charge carriers thermalized to the band edges.
(3) The collection probability for all photogenerated electron-hole pairs at shortcircuit is unity.

(4) The only loss mechanism in excess of the non absorbed photons and the thermalization losses is the spontaneous emission of photons by radiative recombination of electron-hole pairs.

Thus, the photovoltaic process is, when the light with photon energy greater than the band gap is absorbed by the semiconductor material, free electrons and free holes are formed by optical excitation in the semiconductor. The crucial characteristic need for the photovoltaic effect is the presence of some kind of internal electric field that is able to separate the free electrons and holes so that they can pass out of the material into the external circuit before they recombine with one another.

5.3 Description of a photovoltaic device

The general structure of typical solar cell is shown in Fig. 5.1. Fig. 5.2 shows the equivalent circuit for a simple photovoltaic device which includes a current generator corresponding to photoexcitation, a diode containing the internal electric field necessary for driving photoexcited carriers to the external circuit, a series resistance, $R_s$, and a parallel or shunt resistance, $R_{sh}$. To make the model simpler, let us consider it as an “ideal device” with $R_s = 0$ and $R_{sh} = \infty$. If we make the simple assumption that the current generated by light can simply be added to the current flowing in the dark (“superposition”), then the current density ($I$) flowing in the device in the presence of photoexcitation can be expressed as

$$I = I_0 \left[ \exp \left( \frac{qV}{AKT} \right) - 1 \right] - I_L \quad (5.1)$$

Here the first term on the right hand side of Eqn. (5.1) is the forward current driven by the voltage $V$, and the second term is the reverse current associated with photoexcitation. $I_0$ is often
Fig. 5.1: General structure of typical solar cell.
Fig. 5.2: Equivalent circuit of solar cell.
called the “reverse saturation current” of the diode, the value of \( I \) in the dark for large negative values of \( V \) in ideal junctions, which depends on the actual transport mechanism for the diode current and \( A \) is the so-called “ideality factor” that has a value depending on the mechanism of the junction transport (e.g. \( A = 1 \), if the transport process in diffusion; \( A \approx 2 \), if the transport process is recombination in the depletion region). Typical variations of total current \( I \) in both the dark and the light as a function of \( V \) for an ideal solar cell is given in Fig. 5.3. If the voltage is zero (short circuit condition), then of course there is zero current in the dark, but in the light we have,

\[
I_{sc} = -I_L
\]  

(5.2)

and the short-circuit current is controlled only by the photoinduced current generation and the recombination process. If the total current under illumination is zero (open circuit condition), then the solution of Eqn. (5.1) for \( I = 0 \) gives

\[
V_{oc} = \frac{AKT}{q} \ln \left[ \frac{I_L}{I_0} \right] + 1
\]  

(5.3)

Thus the open-circuit voltage is controlled by the current generation and recombination process, but also by the nature of the junction transport currents depending on \( A \) and \( I_0 \). Eqns. (5.2) and (5.3) show the relation between \( I_{sc} \) and \( V_{oc} \) as follows

\[
I_{sc} = I_0 \left[ \exp \left( \frac{qV_{oc}}{AkT} \right) - 1 \right]
\]  

(5.4)

The above equation is exactly similar to Eqn. (5.1) for \( I \) versus \( V \) in the dark condition of ideal junction device. The equivalence of these two dependences is a basic test for the absence of any light-related changes in the parameters entering the equations.

**5.3.1 Parameters of photovoltaic device**
Fig. 5.3: I-V graph of an ideal solar cell.
Various parameters of photovoltaic device are:

(i) Short circuit current and open circuit voltage

The flow of carriers into the external circuit constitutes a reverse electrical current density, \( I \) (A cm\(^{-2}\)), which under short-circuit conditions, is known as the short-circuit current density, \( I_{sc} \). In order to maximize \( I_{sc} \), it is desirable

- To absorb as much of the incident light as possible, i.e. to have a small band gap with high absorption over a wide energy range
- To have material properties in such a way the photoexcited electrons and holes are collected by the internal electrical field and pass into the external circuit before they recombine, i.e. a material with a high minority carrier lifetime and mobility.

The separation of the charges sets up a forward potential difference between the two ends of the material, \( V \), which under open-circuit conditions is known as the open-circuit voltage, \( V_{oc} \). In order to maximize \( V_{oc} \),

- It is preferred to have the forward current driven by the photo-induced potential difference be as small as possible since this current will reduce the potential difference set up by the light.

(ii) Series and shunt resistance

Series resistance is caused by the ohmic losses in the surface of the solar cell. Shunt resistance is caused by the losses due to leakage current in the solar cell. For an ideal cell, series resistance \( (R_s) \) is zero and shunt resistance \( (R_{sh}) \) is in the order of \( \Omega \) cm. Series resistance can be obtained from the inverse of the slope of the I-V graph at \( I \) equal to zero. Whereas, the shunt resistance can be determined from the inverse of the slope of the I-V curve at \( V = 0 \)
Free carrier distribution in (a) homojunction and (b) a heterojunction under forward bias conditions. In homojunctions, carriers are distributed over the diffusion length. In heterojunctions, carriers are confined to the well region.

Fig. 5.4: Difference between homojunction and heterojunction.
(iii) Power maximum, fill factor and efficiency

The efficiency of a photovoltaic solar cell is maximum when the product of the current density $I$ and the voltage $V$ is a maximum. The efficiency $\eta$ itself can be expressed as

$$\eta = \frac{P_m}{P_{rad}} = \frac{I_m V_m}{I_{sc} V_{oc} FF}$$

(5.5)

where $P_{rad}$ is the total radiation power incident on the cell, and $FF$ is called the fill factor; $FF$ is a measure of the “squareness” of the light I-V curve, as shown in Fig. 5.3. $I_m$ and $V_m$ are respectively the values of current density and voltage at the condition corresponding to the maximum power. The definition of the $FF$ can be obtained from Eqn. (5.5),

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

(5.6)

The fill factor for a junction is describable by Eqn. (5.4) which is a function of $A$ and $V_{oc}$, increasing with decreasing $A$ and increasing $V_{oc}$ [5]. The value of $V_m$ can be obtained by multiplying Eqn. (5.1) by $V$ and maximizing the power with respect to $V$.

$$V_m = V_{oc} - \frac{AKT}{q} \ln \left( \frac{qV_m}{AKT} \right) + 1$$

(5.7)

which can be solved iteratively for $V_m$. Using the value of $V_m$, the value of $I_m$, and hence the maximum power $P_m = I_m V_m$, can be obtained from Eqn. (5.1) by substituting $V = V_m$.

5.3.2 Factors influencing the photovoltaic performance

The material properties which are influencing the performance of photovoltaic device are [6]:

- Band gap of the absorbing material. The band gap of the absorbing material must be small enough to allow absorption of an appreciable portion of the solar spectrum, and at the same time large enough to maximize the reverse saturation junction current density $I_0$. 

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Diffusion length of minority carriers. The diffusion length of minority carriers must be as large as possible so that carriers excited by light some distance from the actual semiconductor junction will be able to diffuse to the junction and be collected before they recombine with carriers of the opposite sign. The diffusion length of minority carriers $L_{\text{min}}$ is given by $L_{\text{min}} = (D_{\text{min}} \tau_{\text{min}})^{1/2} = \left[ \frac{kT}{q} \left( \frac{\mu \tau_{\text{min}}}{\min} \right) \right]^{1/2}$, where $D_{\text{min}}$ is the diffusion constant, $\tau_{\text{min}}$ is the life time and $\mu_{\text{min}}$ is the mobility, for minority carriers. It is desired, therefore, to have a material in which the minority carriers have as large a mobility and lifetime as can be obtained. The value of the mobility is more or less determined by the choice of material and does not vary over a wide range. The value of the lifetime, however, is very sensitive to a variety of phenomena in the bulk and at the surface that contribute to recombination of photoexcited carriers. Optimization of efficiency must include solar cell growth and deposition conditions that maximize the minority carrier lifetime. Cell design must include photoexcitation of minority carriers within a diffusion length of the collecting junction.

Desirable junction properties. The actual junction structure and composition determines the magnitude of the junction transport current density $I_0$ and of the ideality factor $A$. Formation of the semiconductor junction must carefully be controlled, therefore, to produce junctions with as low a junction current as possible.

In ideal solar cell, it is assumed that $R_s = 0$ and $R_{sh} = \infty$. But in real solar cells, however, finite values of these two resistances will be present and can be a major factor, particularly in determining the effective value of the $FF$. Contributions to the series resistance $R_s$ can arise both from the resistance of the semiconductor bulk and from the contact resistance to the semiconductor to complete the circuit. Problems involving semiconductor doping and
control of contact resistance can play a significant role in some cases. The parallel resistance $R_{sh}$ can be reduced by grain boundaries or other defects that enhance forward junction current and contribute to an increase in $I_0$ and a decrease in $V_{oc}$. In polycrystalline thin film solar cells, grain boundaries at the junction interface can critically affect junction transport properties.

Solar cells are intended for use in exposed areas for long periods of time without failure. This means that a variety of phenomena that might lead to a decrease in cell efficiency with time of exposure must be carefully considered. In some cases, these instability problems may play a dominant role in determining cell efficiency and utility.

Thus the above said areas of the materials properties must be carefully designed and controlled to maximize the efficiency of an actual solar cell.

### 5.3.3 Heterojunction

There are four different types of semiconductor junctions that have possible application in photovoltaic solar cells, each junction having the fundamental role of supplying the internal electric field needed to separate the photoexcited carriers and to cause them to flow as a current in the external circuit:

1. **Homojunction**
2. **Heterojunction**
3. **Heteroface junction or buried homojunction**
4. **Metal-semiconductor junction (Schottky barrier)**

A $p$-$n$ homojunction is essentially a single semiconductor with two regions of different conductivity type ($n$ and $p$). This junction is formed at the region where the conductivity changes from one type to another. A $p$-$n$ heterojunction is a $p$-$n$ junction formed between two different semiconductors with different band gaps and electron affinities. A typical band diagram for a $p$-$n$
heterojunction is given in Fig. 5.4, which also shows the difference between the homojunction and heterojunction. If the conductivity type is same in the two semiconductors then the heterostructure is called as an isotype. On the other hand, the conductivity of two semiconductors is different then it is called as an anisotype heterojunction. In heterojunction, the $p$-type material is assumed to have a smaller band gap than that of the $n$-type material. If we assume that the doping is of the same magnitude for both $p$- and $n$- type materials, giving equal-width depletion layers on both sides of the junction. The photoexcitation could be either on the $n$-type material (back-wall) or on the $p$-type material (front-wall). Back-wall excitation profits from the larger band gap of the $n$-type material, which acts essentially like a window even for light that is highly absorbed in the $p$-type region, and allows the light to penetrate through to the junction with minimum loss. In order to have better heterojunction, the basic requirements of the semiconductors are: Electron affinities of two materials should be compatible, lattice constant of those semiconductors must nearly be same, and the close thermal expansion coefficients. In the present work, the $p$-$n$ heterojunction ($p$- type CdTe and $n$- type CdS) was formed to study the photovoltaic device performance of the deposited cell structures.

5.4 Results of CdTe, CdTe:Cu, CdS/CdTe, and CdS/CdTe:Cu thin films deposited on FTO substrate

Prior to the photovoltaic study on the p-n heterostructure solar cells, the structural, optical, and luminescence properties of CdTe and CdTe:Cu (2 wt.%, 3 wt.%, 4 wt.%) thin films deposited on FTO substrate have been studied. In addition, the above said properties of $p$-$n$ heterostructure, Glass/FTO/CdS/CdTe or CdTe:Cu were studied. As mentioned earlier, the said films were deposited at different substrate temperatures like RT, 100, 150 and 200°C and then annealed at 400°C. The results are discussed as follows:
5.4.1 Structural property

X-ray diffraction patterns of the CdTe and Cu doped CdTe thin films deposited on FTO substrate at the temperatures of RT, 100, 150 and 200°C and then annealed at 400°C are shown in Fig. 5.5. Meanwhile, the XRD patterns of CdS/CdTe and CdS/CdTe:Cu layers deposited on FTO substrate under the similar conditions are shown in Fig. 5.6. The diffraction patterns show that the films belong to polycrystalline nature. The observed peaks along (111), (200), (220) and (311) orientations are confirmed the cubic phase of CdTe films (JCPDS card Nos.: 65-0880; 89-3011). In addition, the signature of CdS was identified from the small peaks of (100), (103), and (106) orientations (Fig. 5.6) corresponding to the hexagonal phase (JCPDS card No.: 02-0563). Further, the signatures of Te and SnO₂ peaks (due to the substrate) were observed in the XRD patterns. The appearance of Te peak revealed the presence of excess Te in the deposited films, which supports the results of our EDAX and electrical measurements discussed in chapters III and IV. The observed XRD results are in agreement with the reports of Pehnt et al. [7] and Abdullah et al. [8]. The crystallite size of films were evaluated using Scherrer’s formula [9] and the results are summarized in Table 5.1. The degree of crystallinity is high for the RT deposited films and the deterioration in the crystallinity of films deposited at 200°C is due to the possibility of dissociation and desorption of adatoms at higher substrate temperature [10]. Similar to the observation of films deposited on glass substrate (discussed in chapter III), here also we do not observe any complex oxide phases and phase transformation due to the effects of various growth conditions. This revealed the formation of phase pure p-n heterojunction suitable for the photovoltaic device study.
Fig. 5.5: XRD patterns of pure CdTe and Cu doped CdTe thin films deposited on FTO substrate at different substrate temperatures (RT, 100, 150, and 200°C) and then annealed at 400°C. (* denotes SnO₂ peaks).
Fig. 5.6: XRD patterns of FTO/CdS/CdTe and FTO/CdS/CdTe:Cu thin films prepared at different conditions. (* denotes SnO$_2$ peak).
Table 5.1: Crystallite size of CdTe and CdTe:Cu thin films deposited on FTO substrate.

<table>
<thead>
<tr>
<th>Sample conditions</th>
<th>Crystallite size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{sub}} = \text{RT}; T_{\text{annea}} = 400^\circ\text{C}$</td>
<td></td>
</tr>
<tr>
<td>FTO/ CdTe</td>
<td>61</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 2 wt%</td>
<td>41</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 3 wt%</td>
<td>49</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 4 wt%</td>
<td>80</td>
</tr>
<tr>
<td>$T_{\text{sub}} = 100^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C}$</td>
<td></td>
</tr>
<tr>
<td>FTO/ CdTe</td>
<td>54</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 2 wt%</td>
<td>39</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 3 wt%</td>
<td>47</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 4 wt%</td>
<td>53</td>
</tr>
<tr>
<td>$T_{\text{sub}} = 150^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C}$</td>
<td></td>
</tr>
<tr>
<td>FTO/ CdTe</td>
<td>41</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 2 wt%</td>
<td>40</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 3 wt%</td>
<td>43</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 4 wt%</td>
<td>50</td>
</tr>
<tr>
<td>$T_{\text{sub}} = 200^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C}$</td>
<td></td>
</tr>
<tr>
<td>FTO/ CdTe</td>
<td>46</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 2 wt%</td>
<td>45</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 3 wt%</td>
<td>46</td>
</tr>
<tr>
<td>FTO/ CdTe:Cu 4 wt%</td>
<td>52</td>
</tr>
</tbody>
</table>
5.4.2 Optical property

As mentioned earlier, the photovoltaic device performance of an absorber layer depends mainly on its optical energy band gap. In order to evaluate the energy band gap of CdTe, CdTe:Cu, CdS/CdTe, and CdS/CdTe:Cu thin films deposited on FTO substrate, the optical transmittance of the films were measured by UV-Vis-NIR spectrophotometer. During the optical transmission measurements the respective contributions from FTO and FTO/CdS have been nullified by introducing them as the reference and hence the information corresponding to CdTe only was observed. The optical energy band gaps ($E_g$) of films were calculated using Tauc relation discussed in chapter IV. Figs. 5.7 – 5.10 show the Tauc plots of pure and Cu doped CdTe films deposited on FTO substrate at different substrate temperatures of RT, 100, 150, and 200°C and then annealed at 400°C, respectively. Whereas, the Tauc plots of FTO/CdS/CdTe structures prepared at the said respective conditions are shown in Figs. 5.11 – 5.14. The evaluated energy band gap ($E_g$) values are listed in Tables 5.2 (from Figs. 5.7 – 5.10) and 5.3 (from Figs. 5.11 – 5.14). The $E_g$ values are changed from 1.48 to 1.38 eV (Table 5.2) and from 1.57 to 1.38 eV (Table 5.3). Dharmadasa et al. [11] reported the similar band gap values for CdTe layer deposited on FTO substrate for fabricating FTO/CdS/CdTe heterostructure solar cell. In our results, the energy band gap was found to reduce with dopant concentration. This may be attributed to the existence of shallow acceptor level formed by the incorporation of dopant into the CdTe lattice. Since Cu atom is amphoteric nature, it acts as a donor in the interstitial sites and as an acceptor when substituting Cd (Cu$_{\text{Cd}}$). In order to realize p-type doping with optimal transport properties, compensation of Cu$_{\text{Cd}}$ acceptors by Cu$_{\text{i}}$ donors should be avoided [12]. Further, it has been proposed that thermal annealing creates Cd vacancies (V$_{\text{Cd}}$) to facilitate the substitution of Cu atoms in the Cd sublattices [13, 14]. It has been reported that both Cu$_{\text{Cd}}$ and
Fig. 5.7: Tauc plots of pure and Cu doped CdTe thin films deposited on FTO substrate at room temperature and annealed at 400°C.
Fig. 5.8: Tauc plots of pure and Cu doped CdTe thin films deposited on FTO substrate at $T_{\text{sub}} = 100^\circ\text{C}$ and annealed at $400^\circ\text{C}$.

- CdTe: $E_g = 1.47 \text{ eV}$
- CdTe:Cu 2 wt%: $E_g = 1.44 \text{ eV}$
- CdTe:Cu 3 wt%: $E_g = 1.43 \text{ eV}$
- CdTe:Cu 4 wt%: $E_g = 1.42 \text{ eV}$
Fig. 5.9: Tauc plots of pure and Cu doped CdTe thin films deposited on FTO substrate at $T_{\text{sub}} = 150^\circ C$ and annealed at $400^\circ C$.
Fig. 5.10: Tauc plots of pure and Cu doped CdTe thin films deposited on FTO substrate at $T_{\text{sub}} = 200^\circ \text{C}$ and annealed at $400^\circ \text{C}$. 

CdTe:Cu 3 wt%
$T_{\text{sub}} = 200^\circ \text{C}$
$T_{\text{annea}} = 400^\circ \text{C}$
$E_g = 1.45$ eV

CdTe:Cu 2 wt%
$T_{\text{sub}} = 200^\circ \text{C}$
$T_{\text{annea}} = 400^\circ \text{C}$
$E_g = 1.47$ eV

CdTe:Cu 2 wt%
$T_{\text{sub}} = 200^\circ \text{C}$
$T_{\text{annea}} = 400^\circ \text{C}$
$E_g = 1.45$ eV

CdTe:Cu 4 wt%
$T_{\text{sub}} = 200^\circ \text{C}$
$T_{\text{annea}} = 400^\circ \text{C}$
$E_g = 1.43$ eV

The diagrams show the variation of $(a\nu)^2$ with photon energy for CdTe and CdTe:Cu thin films. The slope of the linear portion of the Tauc plot gives the bandgap energy $E_g$. The bandgap values are $1.48$ eV for CdTe, $1.45$ eV for CdTe:Cu 3 wt%, $1.47$ eV for CdTe:Cu 2 wt%, and $1.43$ eV for CdTe:Cu 4 wt% at the specified substrate and annealing temperatures.
Fig. 5.11: Tauc plots of FTO/CdS/CdTe structure prepared at room temperature and then annealed at 400°C.
Fig. 5.12: Tauc plots of FTO/CdS/CdTe structure prepared at $T_{\text{sub}} = 100^\circ \text{C}$ and then annealed at $400^\circ \text{C}$.

- CdTe
  - $T_{\text{sub}} = 100^\circ \text{C}$
  - $T_{\text{anneal}} = 400^\circ \text{C}$
  - $E_g = 1.45 \text{ eV}$

- CdTe:Cu 2 wt%
  - $T_{\text{sub}} = 100^\circ \text{C}$
  - $T_{\text{anneal}} = 400^\circ \text{C}$
  - $E_g = 1.42 \text{ eV}$

- CdTe:Cu 3 wt%
  - $T_{\text{sub}} = 100^\circ \text{C}$
  - $T_{\text{anneal}} = 400^\circ \text{C}$
  - $E_g = 1.40 \text{ eV}$

- CdTe:Cu 4 wt%
  - $T_{\text{sub}} = 100^\circ \text{C}$
  - $T_{\text{anneal}} = 400^\circ \text{C}$
  - $E_g = 1.38 \text{ eV}$
Fig. 5.13: Tauc plots of FTO/CdS/CdTe structure prepared at $T_{\text{sub}} = 150^\circ\text{C}$ and then annealed at $400^\circ\text{C}$. 

- CdTe: Cu 4 wt%, $T_{\text{sub}} = 150^\circ\text{C}$, $T_{\text{anneal}} = 400^\circ\text{C}$, $E_g = 1.42$ eV
- CdTe:Cu 2 wt%, $T_{\text{sub}} = 150^\circ\text{C}$, $T_{\text{anneal}} = 400^\circ\text{C}$, $E_g = 1.44$ eV
- CdTe:Cu 3 wt%, $T_{\text{sub}} = 150^\circ\text{C}$, $T_{\text{anneal}} = 400^\circ\text{C}$, $E_g = 1.43$ eV
- CdTe:Cu 4 wt%, $T_{\text{sub}} = 150^\circ\text{C}$, $T_{\text{anneal}} = 400^\circ\text{C}$, $E_g = 1.46$ eV
Fig. 5.14: Tauc plots of FTO/CdS/CdTe structure prepared at $T_{\text{sub}} = 200^\circ C$ and then annealed at $400^\circ C$.

- **CdTe**: $E_g = 1.44$ eV
- **CdTe:Cu 2 wt%**: $E_g = 1.57$ eV
- **CdTe:Cu 3 wt%**: $E_g = 1.56$ eV
- **CdTe:Cu 4 wt%**: $E_g = 1.48$ eV
Table 5.2: Optical energy band gap values of pure and Cu doped CdTe thin films deposited on FTO substrate.

<table>
<thead>
<tr>
<th>Sample conditions</th>
<th>E_g (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{sub}} = \text{RT}; T_{\text{annea}} = 400^\circ\text{C} )</td>
<td></td>
</tr>
<tr>
<td>FTO/CdTe</td>
<td>1.44</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 2 wt.%</td>
<td>1.42</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 3 wt.%</td>
<td>1.41</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 4 wt.%</td>
<td>1.38</td>
</tr>
<tr>
<td>( T_{\text{sub}} = 100^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C} )</td>
<td></td>
</tr>
<tr>
<td>FTO/CdTe</td>
<td>1.47</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 2 wt.%</td>
<td>1.44</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 3 wt.%</td>
<td>1.43</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 4 wt.%</td>
<td>1.42</td>
</tr>
<tr>
<td>( T_{\text{sub}} = 150^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C} )</td>
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</tr>
<tr>
<td>FTO/CdTe</td>
<td>1.45</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 2 wt.%</td>
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<tr>
<td>FTO/CdTe:Cu 3 wt.%</td>
<td>1.42</td>
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<tr>
<td>FTO/CdTe:Cu 4 wt.%</td>
<td>1.40</td>
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<tr>
<td>( T_{\text{sub}} = 200^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C} )</td>
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</tr>
<tr>
<td>FTO/CdTe</td>
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<tr>
<td>FTO/CdTe:Cu 2 wt.%</td>
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<td>FTO/CdTe:Cu 3 wt.%</td>
<td>1.45</td>
</tr>
<tr>
<td>FTO/CdTe:Cu 4 wt.%</td>
<td>1.43</td>
</tr>
</tbody>
</table>
Table 5.3: Optical energy band gap values of FTO/CdS/CdTe structures.

<table>
<thead>
<tr>
<th>Sample conditions</th>
<th>$E_g$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$T_{sub}$ = RT; $T_{annea}$ = 400°C</strong></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>1.44</td>
</tr>
<tr>
<td>CdTe:Cu 2 wt.%</td>
<td>1.42</td>
</tr>
<tr>
<td>CdTe:Cu 3 wt.%</td>
<td>1.42</td>
</tr>
<tr>
<td>CdTe:Cu 4 wt.%</td>
<td>1.41</td>
</tr>
<tr>
<td><strong>$T_{sub}$ = 100°C; $T_{annea}$ = 400°C</strong></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>1.45</td>
</tr>
<tr>
<td>CdTe:Cu 2 wt.%</td>
<td>1.42</td>
</tr>
<tr>
<td>CdTe:Cu 3 wt.%</td>
<td>1.40</td>
</tr>
<tr>
<td>CdTe:Cu 4 wt.%</td>
<td>1.38</td>
</tr>
<tr>
<td><strong>$T_{sub}$ = 150°C; $T_{annea}$ = 400°C</strong></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>1.46</td>
</tr>
<tr>
<td>CdTe:Cu 2 wt.%</td>
<td>1.44</td>
</tr>
<tr>
<td>CdTe:Cu 3 wt.%</td>
<td>1.43</td>
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<tr>
<td>CdTe:Cu 4 wt.%</td>
<td>1.42</td>
</tr>
<tr>
<td><strong>$T_{sub}$ = 200°C; $T_{annea}$ = 400°C</strong></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>1.44</td>
</tr>
<tr>
<td>CdTe:Cu 2 wt.%</td>
<td>1.57</td>
</tr>
<tr>
<td>CdTe:Cu 3 wt.%</td>
<td>1.56</td>
</tr>
<tr>
<td>CdTe:Cu 4 wt.%</td>
<td>1.48</td>
</tr>
</tbody>
</table>
$V_{Cd}$ are acceptors located at 0.22 eV and 0.13 eV, respectively, above the valence band [15]. Hence from our observations, the dopant Cu acts as substitutional impurity in the Cd vacancy i.e. $Cu_{Cd}$, since it is been identified as a $p$-type material from the EDAX and electrical studies. Thus the shrinkage of energy band gap is due to the formation of shallow acceptor levels (both $Cu_{Cd}$ and $V_{Cd}$). Hu et al. [16] reported the substrate temperature induced broadening of $E_g$ for CdTe thin films deposited on FTO substrate and the reported $E_g$ values are in the range of present work. In addition, Ding et al. [17] have observed the band gap narrowing for CdTe thin films deposited with different substrate temperatures.

5.4.3 Photoluminescence property

The optical quality of CdTe, CdTe:Cu, CdS/CdTe, and CdS/CdTe:Cu films deposited on FTO substrate was further studied by photoluminescence spectroscopy. All the samples were excited at 600 nm. Figs. 5.15 and 5.16 show the photoluminescence spectra of FTO/CdTe and FTO/CdS/CdTe structure respectively. The existence of single emission peak localized around 822 nm corresponds to the band to band radiative recombination, which revealed the characteristic feature of CdTe. This is in line with the result of UV-Vis-NIR spectrophotometer measurement. Similar change in intensity of PL peak has been observed as in the case of films deposited on glass substrate (chapter IV), which may be due to the variation in surface state density.

These results revealed the suitability of prepared $p$-$n$ heterostructure for the photovoltaic device applications.
Fig. 5.15: Photoluminescence spectra of pure and Cu doped CdTe thin films on FTO substrate at different substrate temperatures: a = RT, b = 100°C, c = 150°C and d = 200°C, and then annealed at 400°C.
Fig. 5.16: Photoluminescence spectra of FTO/CdS/CdTe or CdTe:Cu (Cu = 2, 3, 4 wt%) heterostructure at different substrate temperatures: a = RT, b = 100°C, c = 150°C and d = 200°C, and then annealed at 400°C.
5.5 Glass/TCO/CdS/CdTe/Au solar cell

5.5.1 Construction of $p$-$n$ heterostructure solar cell

The schematic sketch for the construction of $p$-$n$ heterostructure solar cell is shown in Fig. 5.17. The transparent ordinary window glass (about 2 – 3 mm thick) was used to protect the active layers from the environment. The transparent conducting oxide of FTO was used as a front contact of the device because of its high work function and larger mechanical stability. In addition, the FTO reduces the series resistance of the device, which would otherwise arise from the thinness of the window layer. Thin layer of $n$-CdS (about 100 nm) was used as the window layer of the device owing to its wide band gap and transparent nature down to the wavelength of about 500 nm. The $p$-CdTe (1 μm thick) was used as an active absorber layer. It is the effective region of the device, where the generation and collection of carriers occur. The back contact provides a low resistance electrical connection to the CdTe. Gold (Au) (few tens of nm thick) was used as back contact on CdTe layer. This construction of solar cell is called the superstrate configuration.

The current-voltage (I-V) characteristics of this cell structures were measured using the solar simulator (4200 Keithley Semiconductor Characterization System). Photocurrent was measured by illuminating the white light using a halogen lamp. The conversion efficiency of the cell was measured with a power density of 100 mW/cm$^2$. The photo response of the solar cell was measured by varying the power intensity (60, 80, and 100 mW/cm$^2$).

5.5.2 I-V characteristics

The current-voltage (I-V) characteristics of the cell (Glass/TCO/CdS/CdTe/Au) prepared at the substrate temperatures of RT, 100, 150 and 200°C are shown in Figs. 5.18 – 5.21, respectively. Also, the photo response of the cell doped with 4 wt.% of Cu studied by varying the
Fig. 5.17: The schematic sketch for the construction of p-n heterostructure solar cell.
Fig. 5.18: I-V curve of the cell structure prepared at RT and annealed at 400°C.

$T_{\text{sub}} = \text{RT}; T_{\text{annea}} = 400^\circ\text{C}$

$P_{\text{in}} = 100 \text{ mW/cm}^2$

- Pure CdTe
- CdTe:Cu 2 wt%
- CdTe:Cu 3 wt%
- CdTe:Cu 4 wt%
Fig. 5.19: I-V curve of the cell structure prepared at 100°C and annealed at 400°C.

$T_{\text{sub}} = 100^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C}$

$P_{\text{in}} = 100$ mW/cm$^2$
Fig. 5.20: I-V curve of the cell structure prepared at 150°C and annealed at 400°C.

- Pure CdTe
- CdTe:Cu 2 wt%
- CdTe:Cu 3 wt%
- CdTe:Cu 4 wt%

\[ T_{\text{sub}} = 150^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C} \]

\[ P_{\text{in}} = 100 \text{ mW/cm}^2 \]
Fig. 5.21: I-V curve of the cell structure prepared at 200°C and annealed at 400°C.

- $T_{\text{sub}} = 200^\circ\text{C}$; $T_{\text{annea}} = 400^\circ\text{C}$
- $P_{\text{in}} = 100 \text{ mW/cm}^2$

- Pure CdTe
- CdTe:Cu 2 wt%
- CdTe:Cu 3 wt%
- CdTe:Cu 4 wt%
Fig. 5.22: Photo response of the cell structure prepared at RT and annealed at 400°C.

$T_{sub} = RT; T_{annea} = 400^\circ C$

Sample - CdTe:Cu 4 wt%

- $60 \text{ mW/cm}^2$
- $80 \text{ mW/cm}^2$
- $100 \text{ mW/cm}^2$

Current density (mA/cm$^2$) vs. Anode voltage (V)
Fig. 5.23: Photo response of the cell structure prepared at 100°C and annealed at 400°C.

Sample - CdTe:Cu 4 wt%

$T_{\text{sub}} = 100^\circ\text{C}; T_{\text{annea}} = 400^\circ\text{C}$
Fig. 5.24: Photo response of the cell structure prepared at $150^\circ$C and annealed at $400^\circ$C. Sample = CdTe:Cu 4 wt%
Fig. 5.25: Photo response of the cell structure prepared at 200°C and annealed at 400°C.

Sample = CdTe:Cu 4 wt%

$T_{\text{sub}} = 200^\circ\text{C}$; $T_{\text{annea}} = 400^\circ\text{C}$

Anode voltage (V)

Current density (mA/cm$^2$)

- 60 mW/cm$^2$
- 80 mW/cm$^2$
- 100 mW/cm$^2$
power density of 60, 80 and 100 mW/cm² are shown in Figs. 5.22 – 5.25. The span of the I-V curve ranges from the short circuit current ($I_{sc}$) at zero volts, to zero current at the open circuit voltage ($V_{oc}$). The ‘knee’ of the I-V curve is the maximum power point ($I_{max}$, $V_{max}$), the point at which the solar cell generates maximum electrical power. At voltages well below $V_{max}$, the flow of photogenerated electrical charge to the external circuit is relatively independent of output voltage. Near the knee of the curve, this behavior starts to change. As the voltage increase further, an increasing percentage of the charges recombine within the solar cells rather than flowing out through the external circuit. At $V_{oc}$, all of the charges recombine internally. The maximum power point, located at the knee of the curve, is the ($I$, $V$) point at which the product of current and voltage reaches its maximum value.

The various solar cell parameters such as open circuit voltage ($V_{oc}$), short circuit current ($I_{sc}$), fill factor ($FF$), efficiency ($\eta$), series resistance ($R_s$) and shunt resistance ($R_{sh}$) were evaluated from the I-V curve and the results are summarized in Table 5.4. It is observed from the table that the open circuit voltage ($V_{oc}$) varies between 290 and 643 mV and the short circuit current density changes from 2.87 to 4.75 mA/cm². It is also seen that the open circuit voltage ($V_{oc}$), short circuit current density ($I_{sc}$) and fill factor ($FF$) increase with increasing Cu concentration. This may be due to the suitable incorporation of Cu into the host lattice and also due to the formation of acceptor level through the dopant. This can be explained as, the Cu dopant may increase the free carrier concentration, due to the substitutional incorporation of Cu$^{2+}$ ions instead of Cd$^{2+}$ ions [18]. In addition, it was reported that the increase in resistivity ($\rho$) of CdTe layer leads to the decrease in open circuit voltage [19]. This is indeed true in our case as well, where the open circuit voltage increases with the decrease in resistivity of the film. This is because, as resistivity ($\rho$) varies, the factor $\Delta\mu$, (the energy spacing between the Fermi level and
Table 5.4: Solar cell parameters of the Glass/TCO/CdS/CdTe/Au cell structures.

<table>
<thead>
<tr>
<th>Samples and conditions</th>
<th>$V_{oc}$ mV</th>
<th>$I_{sc}$ mA/cm$^2$</th>
<th>$V_{max}$ mV</th>
<th>$I_{max}$ mA/cm$^2$</th>
<th>FF</th>
<th>$\eta$ (%)</th>
<th>$R_s$ $\Omega$cm$^2$</th>
<th>$R_{sh}$ $\Omega$cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{sub} = RT; T_{annea} = 400^\circ C$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure CdTe</td>
<td>576</td>
<td>3.52</td>
<td>376</td>
<td>2.83</td>
<td>0.53</td>
<td>1.07</td>
<td>60.7</td>
<td>825</td>
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<td>398</td>
<td>3.40</td>
<td>0.51</td>
<td>1.35</td>
<td>50.3</td>
<td>909</td>
</tr>
<tr>
<td>CdTe:Cu 3 wt%</td>
<td>620</td>
<td>4.52</td>
<td>406</td>
<td>3.66</td>
<td>0.53</td>
<td>1.48</td>
<td>44.9</td>
<td>946</td>
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<td>CdTe:Cu 4 wt%</td>
<td>643</td>
<td>4.60</td>
<td>476</td>
<td>3.55</td>
<td>0.57</td>
<td>1.68</td>
<td>31.4</td>
<td>953</td>
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<td></td>
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<tr>
<td>Pure CdTe</td>
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<td>2.91</td>
<td>314</td>
<td>2.21</td>
<td>0.52</td>
<td>0.69</td>
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<td>3.26</td>
<td>344</td>
<td>2.27</td>
<td>0.52</td>
<td>0.78</td>
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<td>0.96</td>
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<td>4.14</td>
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<td></td>
</tr>
<tr>
<td>Pure CdTe</td>
<td>550</td>
<td>4.09</td>
<td>390</td>
<td>3.05</td>
<td>0.53</td>
<td>1.19</td>
<td>32.5</td>
<td>496</td>
</tr>
<tr>
<td>CdTe:Cu 2 wt%</td>
<td>576</td>
<td>4.40</td>
<td>387</td>
<td>3.37</td>
<td>0.52</td>
<td>1.32</td>
<td>29.2</td>
<td>496</td>
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<tr>
<td>CdTe:Cu 3 wt%</td>
<td>594</td>
<td>4.61</td>
<td>431</td>
<td>3.49</td>
<td>0.55</td>
<td>1.51</td>
<td>26.7</td>
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<tr>
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<td>4.75</td>
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<td>0.53</td>
<td>1.53</td>
<td>34.8</td>
<td>620</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pure CdTe</td>
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<td>2.87</td>
<td>229</td>
<td>1.60</td>
<td>0.44</td>
<td>0.36</td>
<td>23.5</td>
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</tr>
<tr>
<td>CdTe:Cu 2 wt%</td>
<td>304</td>
<td>3.23</td>
<td>214</td>
<td>2.20</td>
<td>0.48</td>
<td>0.47</td>
<td>20.6</td>
<td>308</td>
</tr>
<tr>
<td>CdTe:Cu 3 wt%</td>
<td>309</td>
<td>3.59</td>
<td>220</td>
<td>2.50</td>
<td>0.49</td>
<td>0.54</td>
<td>17.0</td>
<td>326</td>
</tr>
<tr>
<td>CdTe:Cu 4 wt%</td>
<td>318</td>
<td>3.75</td>
<td>243</td>
<td>2.56</td>
<td>0.52</td>
<td>0.62</td>
<td>15.5</td>
<td>341</td>
</tr>
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</table>
the top of the valence band) varies, thus affecting the value of the recombination current. The observed larger $V_{oc}$ for the cell structure prepared at $T_{sub} = RT$ and $T_{annea} = 400^\circ C$ may be due to the grain boundary effect owing to the degree of crystallinity. The grain boundaries are considered as active recombination centers in CdTe. This is consistent with our XRD data, where we observe the large crystallite size for the cell prepared at $T_{sub} = RT$ and $T_{annea} = 400^\circ C$. The conversion efficiencies ($\eta$) of the cells are vary between 0.36 and 1.68%. However, the lower short circuit currents are responsible for the low conversion efficiency values.

The observed low value of short circuit current may be attributed to the surface recombination. This may be explained as follows: the absorption coefficient ($\alpha$) of CdTe steeply increases in a narrow range $h\nu \approx E_g$ and becomes higher than $10^4$ cm$^{-1}$ at $h\nu > E_g$. As a result, the penetration depth of photons ($\alpha^{-1}$) is less than $\sim$ 1 $\mu m$. When the electric field in the space charge region is not strong enough, these photogenerated electrons may recombine before running through the external circuit and hence lowers the short circuit current [19]. In addition, it was stated that the short circuit current density will be lower if a significant portion of radiation is absorbed outside the space-charge region [19].

Further, the diffusion component of the short circuit current depends on the thickness of CdTe layer. The losses of the diffusion component of the short-circuit current are 5, 9 and 19% for 10, 5 and 2 $\mu$m of the CdTe film layer, respectively [19]. The higher the thickness, the lower the losses of diffusion component. In our case, the thickness of CdTe layer is 1 $\mu$m from which the losses of the diffusion component of the short circuit current may be expected more since because of the higher absorption coefficient ($> 10^4$ cm$^{-1}$) and hence lower penetration depth ($< 1 \mu$m) [19]. Thus, the carriers arisen outside the space-charge region diffuse into the neutral part of the CdTe layer penetrating deeper into the material. Carriers reached the back surface of the
layer, recombine and do not contribute to the photocurrent. If the layer thickness is low, recombination may take place even at the back surface which annihilates the photogenerated electrons. Thinning of CdTe layer reduces the short circuit current density, due to the incomplete charge collection in the neutral part of the CdTe film. Besides if the space charge region is too wide, the electric field becomes weak and the short circuit current is reduced due to recombination at the front surface. However, observation of this measurable current flow is due to the grain growth attained by the post-deposition heat treatment of the fabricated CdS/CdTe heterostructure. This reduces the defect density, grain boundaries (which acts as recombination centers in CdTe) and promoted the interdiffusion between the CdTe and CdS layers that reduces the recombination rate to some extent [20].

Series resistance ($R_s$) is caused by the ohmic losses in the surface of the solar cell. The parallel shunt resistance ($R_{sh}$) is caused by the losses due to leakage current in the solar cell [21]. For the ideal cell, the series resistance ($R_s$) is zero and shunt resistance ($R_{sh}$) is in the order of MΩ cm. From our results, it is observed that both the ohmic losses through the higher series resistance and leakage current loss through the lower shunt resistance may be the reason for the collection of lower short circuit current and conversion efficiency. However, the decrease in series resistance and the increase in shunt resistance with respect to the increasing Cu concentration leads to the increase in $I_{sc}$ and efficiency. Paudel et al. [22] reported the similar ranges of shunt resistance and fill factor values for CdS/CdTe solar cells. Madhu et al. [23] have reported the $V_{oc}$ of 209 mV, $I_{sc}$ of 2.3 mA/cm$^2$, $FF$ of 0.3, and the efficiency of 1.88% for the electrochemical deposited CdS/CdTe solar cell. However the photoresponse of the device is good as the $V_{oc}$ and $I_{sc}$ is increased with increase in input power as observed from Figs. 5.22 – 5.25. The observed solar cell parameters are comparable with the literature.
5.6 Conclusions

The structural and optical properties of pure CdTe, Cu doped (2, 3 and 4 wt.%) CdTe, CdS/CdTe, and CdS/CdTe:Cu layers deposited on transparent conducting oxide substrate were studied. The films exhibit polycrystalline with cubic zinc blende structure for CdTe and hexagonal phase for CdS. Crystallite size was higher for the samples deposited at room temperature and annealed at 400°C. The non-existence of oxide peaks and other elemental peaks except Te inferred the phase pure nature of the cell structure. The photoluminescence study further confirmed the optical quality of the cell structures. The Cu concentration induced decrease in band gap values of the samples was observed. The I-V characteristics of the heterojunction solar cell structures have been studied by illuminating the white light using a halogen lamp. The observed low efficiency of the solar cells may be due to the nature of CdTe and CdS layers, junction formation, and grain boundary effects.

In addition, the low value of $I_{sc}$ may be because the internal electric field is not strong enough to keep the freed electrons and holes to pass through the external circuit and also due to the low minority carrier lifetime which lead to the recombination losses. Moreover, the efficiency is increased with increasing Cu concentration and the cell prepared at RT with 4 wt.% of Cu addition possess the maximum conversion efficiency of 1.68%. Further, the photoresponse of the device is good as the $V_{oc}$ and $I_{sc}$ is increased with increase in input power.

Based on these results, it may be concluded that the CdTe based heterojunction solar cell prepared in the present work possess the I-V characteristics, which are of suitable for photovoltaic device applications.
References


