Physical Properties of $SrCl_2$ Coated CdTe Thin Film for Photovoltaic Applications

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Thin films.

Solar cells

Spin coating.

X-Ray diffraction.

Ellipsometry

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Physical Properties of $SrCl_2$ coated CdTe Thin Film for Photovoltaic Applications

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It is certified that the work presented in this thesis entitled "Physical Properties of $SrCl_2$ coated CdTe Thin Film for Photovoltaic Applications" by Gohar Awais Mustaq Hashmi, Registration No. 265-FBAS/MSPHY/S14 fulfils the requirement for the award of degree of MS Physics from Department of Physics, International Islamic University, Islamabad, Pakistan.

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Gohar Awais Mustaq Hashmi
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Certificate

It is certified that work contained in this thesis is carried out by Gohar Awais Mushtaq Hashmi under my supervision at the Department of Physics, International Islamic University, Islamabad, Pakistan.

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Dedicated to my

Respected parents

&

Beloved Elder brother

Atif Sajjad Nomi

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Abstract

Cadmium telluride (CdTe) has long been recognized as an absorber layer for solar cell fabrication. The $CdCl_2$ treatment is one of the key step for CdTe based solar cell, which increases efficiency and quality of solar cell. However, $CdCl_2$ is expensive, toxic and not environment friendly. In this work we have proposed strontium chloride $SrCl_2$, as an environment friendly replacement for $CdCl_2$ coating. This proposed material is non-toxic, abundant and environment friendly and may provide better efficiency to solar cell. CdTe thin films were prepared by closed space sublimation (CSS) technique on glass substrate and $SrCl_2$ was further coated on these thin films by Spin Coating technique. The samples were annealed at 200°C. Structural analysis including particle size, dislocation density and strain were determined by XRD. Surface morphology is observed by SEM images. Band gaps were determined by spectroscopic ellipsometry. I-V characteristics is used for electrical properties and optical properties were determined by Spectroscopic Ellipsometry technique. The $SrCl_2$ coated thin films are comparable and environmental friendly replacement for the $CdCl_2$ coated CdTe thin films.

CHAPTER 01

Introduction

1.1 Introduction

Photo-voltaic conversion of solar energy is most important way to meet the increasing energy demands in a time when formal energy sources being drained off. Solar energy has less environmental impact than formal energy sources. Formal energy methods produce pollutants like CO_2, CO, oxides of sulphur and nitrogen oxides etc. that provides foundation to greenhouse effect and global warming [1]. Solar energy is a renewable, non-polluting substitute for formal energy sources with considering long life [2]. However, solar energy has comparatively high installing cost. But, it can be recompense by life time of solar cell.

A solar cell relies on a quantum mechanical process known as the "photovoltaic (PV) effect". Solar cell efficiency and performance relies on the material used in cell, design and manufacturing process. Different kinds of solar cells are single junction cells, multi-junction cells, crystalline Si cells and thin film cells etc. Well efficient semiconductor materials are single crystalline silicon (Si), amorphous Si and polycrystalline thin films are used in solar cells. Among polycrystalline thin films, copper-indium-diselenide ($CuInSe_2$) and cadmium-telluride (CdTe) are the most popular.

1.2 Background

A.E. Becquerel observed photovoltaic effect when he was investigating by light fall on electrode in electrolytic solution, voltage created [3, 4]. After 50 years, first solar cell by using junction was formed by selenium coated with ultra-thin gold layer [5]. But, these devices were not efficient, only to convert less than 1% of light. In 1927, Solar cell formed by copper and copper oxide was introduced [6]. In 1930s photo sensitive devices used selenium and copper oxide cell but, these cell had problems in efficiency, which was >1%. The problem was solve by the formation of the Si solar cell by Resell in 1941 [7]. A single crystal silicon (sc-Si) PV cells of 6% efficiency was made in 1954 at Bell Laboratories. Gallium arsenide (GaAs) were manufactured in late 1980 with 20% efficient. Since 1990, 12% and 7% efficiency was recorded for 7% amorphous Si and 12% polycrystalline thin film in lab and in commercial cell respectively. In 1992, the University of South Florida fabricated thin film SnO_2/CdS/CdTe cell with 15.8% efficiency [8]. In 2002, the CdTe devise structure was modified by NREL and manufactured the Cd_2SnO_4/Zn_2SnO_4/CdS/CdTe thin-film solar cell with 16.4% efficiency [9].

About 30% efficiency was recorded for concentrator solar cell which use lenses for concentrating sunlight on special Si cell. GaAs is used in multi junction cell which gives efficiency greater than 20% under concentrated light [10].

1.3 The Principle of Solar Cell

Conversion of energy from incident photons directly into electricity using solar cells is called the process of photovoltaics. When light is absorbed by semiconductor material, the incident photons create electron-hole pair [11]. Therefore, holes are created in valence band when electron was excited from valence band to conduction band. In addition, the electron can be easily reached to conduction band in direct band gap semiconductors while some energy is used for indirect band gap.

The majority carriers are holes and electrons inside the p and n type semiconductors respectively. There are two types of p-n junctions. The first one is the homojunction and second one is the heterojunction. In homojunction, the semiconductors with different doping was brought together to form p-n junction, while in heterojunction two different types of semiconductors brought together to form p-n junction [12, 13].

The holes move from the p- side to the n- side. The process of diffusion would not stop until the concentration of holes and electrons on both sides reach equilibrium state. The result of these movements is to form the p-n junction

1.4 CdTe based Solar cells

Since 1954, the first 6% silicon solar cell was introduced by Chapin [14], the photovoltaic technology has been grown in numerous ways, using different materials. Each technology have different features e.g. conversion efficiency, cost, stability, application, etc. In this paragraph, a brief overview of most extensive and liable photovoltaic technologies will discuss i.e. thin film solar cells. Thin films solar cells efficiency progressively increases with decrease in cost. Since 2007 they captures a remarkable place in the whole PV market. Figure 1.1.

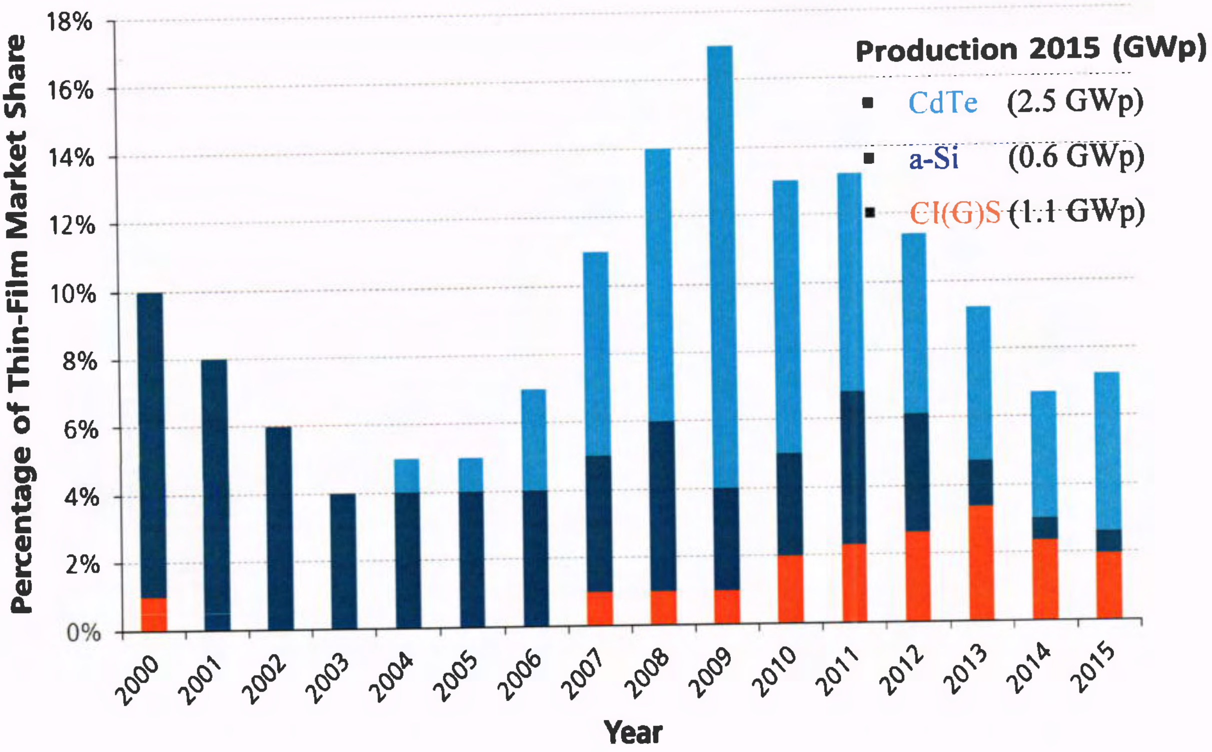


Figure 1. 1 Thin Film in PV market [15]

Copper indium gallium (di) selenide (CIGS) is one of the well-known thin film technologies having high conversion efficiency and comparatively low production cost. CIGS is well known as flexible modules production for maintaining efficiency. Highly efficiency 20.4% was achieved on flexible substrates by EMPA labs [16]. The main drawback is the insufficiency of indium. However, cells are being furnished by replacing selenium with sulphur ($CIGS_2$) [17].

Cadmium telluride is currently the most promising material for high efficiency, low-cost thin-film solar cells. Cadmium telluride has an ideal 1.45 eV bandgap for direct light-to-electricity conversion. CdTe has high light absorption coefficient to absorb 99% of visible light. Fabrication of CdTe thin film seems to be less critical than other semiconductor materials. CdTe gives real substitute to silicon in PV market. It attains 17% share of PV market in 2009 and still on top. The cell conversion efficiency achieved is 18.7 % [18] [16] while for modules is 15.3 % [17], this values state the high scalability of the production process. On the other hand, CdTe are the lowest in cost in PV market about (0,67 \$/Wp) [19], that is the actual strength of CdTe as shown in the Figure 1.2.

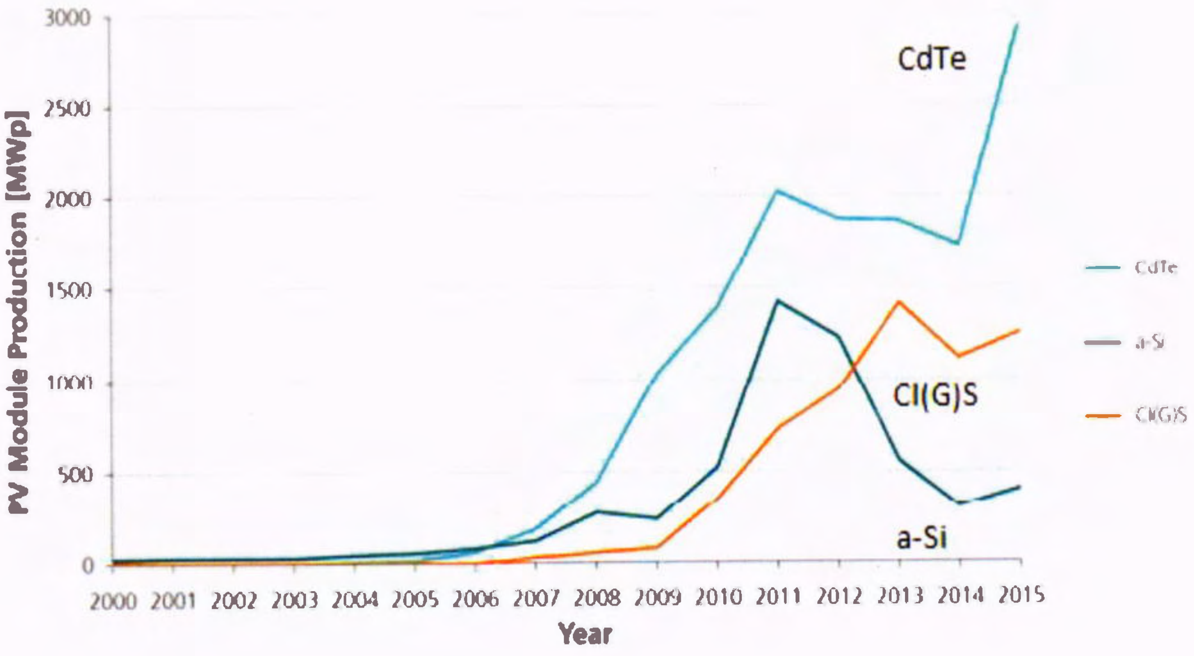


Figure 1. 2 PV Module Production [15]

However, CdTe has some flaws also i.e.

- Te rarity,
- Cd toxicity,
- Back-contact stability.

Tellurium is a rare metalloid. Cadmium is toxic and if inhaled in fine dust or fumes, that a critical factor about CdTe in the market. However, CdTe is very stable compound, can't be soluble in water and having high melting temperature (1092°C), and hence in short, it is absolutely harmless. Nowadays, modules are produced usually with a thickness of around 4µm that means 28 g/m^2 of CdTe. It has been considered that reducing the CdTe thickness down to 1 µm can solve the problem of Te abundance up to a yearly production of 100 GW [20] and, at the same time, this reduced the Cd amount also to 2.7 g/m^2, almost ten times smaller than C-size Ni-Cd rechargeable batteries [21]. Moreover, CdTe modules are generally stable for 20-25 years. Its efficiency cannot decrease less than 80 % of its initial values. The installation cost and efficiency comparison of different modules are given below in Figure1.5.

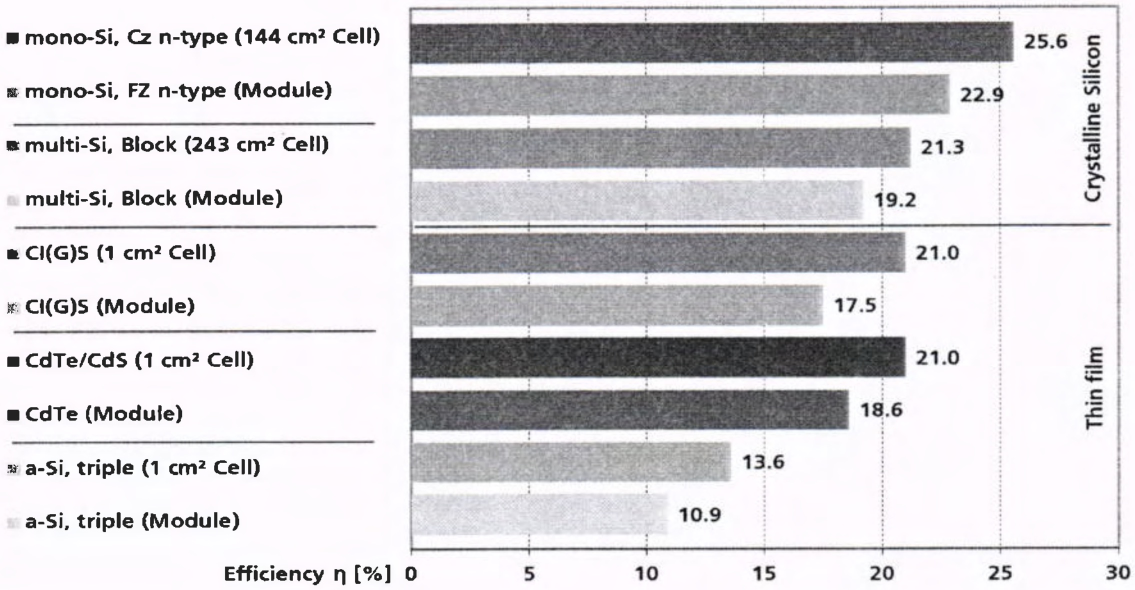


Figure 1. 3 Modules Efficiency Ꞃ [%] [15]

1.5 $CdCl_2$ treatment for CdTe based solar cells

In CdTe solar cell, fabrication, $CdCl_2$ treatment has been well known to significantly increase the conversion efficiency of cell [22-23]. Besides, improving the efficiency of cell, CdTe thin films may convert from p-type to n-type by $CdCl_2$ treatment [24, 25] with enhancement of n-type conductivity [26]. There are also recent reports of conversion of p-type CdTe to n-type [23, 27, 25] or at least converting the p-type grains in to n-type grains of CdTe [28] and thin outer layer of n-CdTe to p-type [27]. However, it depend on the nature of the defect distribution in the as-grown CdTe material. This treatment contains post-growth of $CdCl_2$ on CdTe layer by using solution of $CdCl_2$ in methanol or water. Furthermore, it annealed from 350–450°C for 20-60 min in vacuumed conditions. Alternatively, it can be achieved by evaporating $CdCl_2$ powder on CdTe layers. This post growth treatment remarkably improves efficiency from about 1%–5% to 15% to 20% for $CdCl_2$-treated materials. A lot of researches had been done to realize the logic behind this activation step. For this reason, some of the publications label this as an "empirical magic production step" [29].

1.6 Problem & Goals of this research work

No doubt that post growth treatment of $CdCl_2$ increases the efficiency of CdTe based solar cell. But, there are some issues with it that makes them critical in PV market i.e. CdTe and CdS are highly stable in atmosphere and are not soluble in water to produce cadmium ions. Unlike, $CdCl_2$ is soluble in water and produces toxic Cd ions that are hazardous for both the production works and for the environment and also it is costly as compared to other.

Recently, it has been demonstrated that direct replacement of toxic and costly $CdCl_2$ replaced by $MgCl_2$, $ZnCl_2$ and NH_4Cl produces suitable alternative results. Interestingly, some other salts NaCl, KCl, HCl and $MnCl_2$ was also investigated for getting higher efficiency but, was considerably less successful. Achieved efficiency of these compounds are given below in the Table 1.1.

Table 1. 1 Ultimate efficiencies attained for different chloride treatments [30, 31]

Materials	**Efficiency [%]**	**Open-circuit voltage [V]**	**Short-circuit current [mA cm $^{-2}$]**	**Fill factor [%]**
$CdCl_2$	13.02	0.831	22.13	70.01
$MgCl_2$	12.71	0.821	22.41	69.08
NH_4Cl	10.31	0.804	22.02	63.29
HCl	8.24	0.700	20.37	57.80
NaCl	6.75	0.603	19.78	53.34
KCl	5.49	0.607	17.95	50.11
$MnCl_2$	4.37	0.520	18.30	45.87

In this work, I will investigate the effect of the coating of $SrCl_2$ on CdTe thin film layer for better efficiency and good replacement for $CdCl_2$ as $SrCl_2$ is non-toxic and low cost also and easily available in market.

CHAPTER 2

Literature Review

CdTe based solar cells were studied comprehensively by researchers. Different methods and techniques and treatments were used for fabrications of CdTe which effects on structural, optical and electrical properties of solar cell. In this chapter, we have summarised the methods, treatments and their effects on CdTe solar cells.

2.1 Literature Review

Sr No	Material & Structures	Method of preparation	Annealing Conditions	Major Findings	Ref
1	CdTe thin film with $CdCl_2$ coating	Close Spaced Sublimation (CSS)	400 °C for 30 min at 10^{-3} mbar Pressure	Effected Optical, electrical and surface morphology	32
2	CdTe thin film With Cu-coating	Two source evaporation technique	Double annealed 500 °C for 60 min at 10^{-3} mbar	Hard CdTe films were produced, there were decrease in transmission and refractive index increases & change in optical band measured.	33
3	CdTe thin film With Cd-doping	Close Spaced Sublimation (CSS)	350 °C for 30 min at 10^{-3} mbar	CD-composition increasing with doping Cd. The lattice constant decreases and affecting transmittance, resistivity decreases with doping and conductivity increases.	34
4	CdTe thin film With Cu-doping	Vacuum evaporation technique	450 °C for about 4-6 min	Morphology of thin film, grain size, and electrical properties changed significantly. Optical absorption and band gap not so much effected	35

5	CdTe/CdS Heterojunction solar cell with Quasi-gaseous $CdCl_2$ instead of $CdCl_2$ solution	Chemical Bath Deposition method, Quasi-gaseous method	450°C for 60min	Gives better physical properties to these obtained using the conventional solution CdCl2 treatment	36
6	CdTe polycrystalline thin film with Cd & Te doping	Close Space Sublimation (CSS)	300°C for 30 min at 10^{-3}mbar	n-type doping can be achieved when interstitial Cd atoms are incorporated in the CdTe lattice	37
7	ITO/CdTe/CdS thin film with $CdCl_2$ treatment	Close Space Sublimation And Chemical bath deposition method	400°C for 30 min with constant flow of argon gas(30 ml/min)	Significant improvement to the CdTe/CdS film solar cell performance can be achieved	38
8.	CdTe/CdS with Freon Gas ($HCFCl_2$) instead of $CdCl_2$	RF-Sputtering in Ar+CHF_3 And Close Space Sublimation (CSS)	Pressure range for freon gas is 10-30 mbar and for Ar is 100-500 mbar	As a source of Cl containing inert gas suitable to make CdTe films thermal treatment both Chlorofluorocarbons and hydrocarbons may be used.	39
9.	ZTO/CTO/CdS/CdTe polycrystalline thin film with Vapour $CdCl_2$ treatment	Chemical bath deposition (CBD), Rf magnetron sputtering and close space sublimation (CSS)	400°C-430°C for 15 mins	Highest efficiency achieved (16.5 %). The use of CTO/ZTO/CdS/CdTe device structure improves device performance and reproducibility.	40

10.	CdTe thin film with Cu doping	Close Spaced Sublimation, Ion Exchange process	500±5°C on 10^{-3} mbar pressure, chemical treatment of $Cu(NO_3)_2.H_2O$ (1g/1L) with altered time interval as 0, 15min, 1h, 3h, 15h.	Change in surface morphology, optical properties, electrical properties measured by immersion of CdTe films in $Cu(NO_3)_2.H_2o$. It also affected the intensity of XRD peaks also increases the quantity of Cu in film	41
11.	CdS/CdTe solar cell with Freon gas treatment (HCF_2Cl)	Rf magnetron sputtering , close space sublimation (CSS)	Total pressure 400-800 of mixture of gases (oxygen-argon) with 50 mbar partial pressure of Freon gas. Heated at 400°C for 5 mins	Obtained highly efficient solar cells (14% in 0.21 cm^2) and inert and nontoxic gas at room temperature is used	42
12.	CdTe thin film with $CdCl_2$ treatment	Thermal evaporation and dip coating	Heated on 400°C for 15mins at 200-250 torr pressure	Changes occur in structural, morphological, optical, and electrical properties	43
13.	CdTe thin film with $Cu(NO_3)_2.H_2O$ treatment	Close space sublimation (CSS), Dip coating	Double annealed at 400°C for 30mins before and after dip coating of $Cu(NO_3)_2.H_2O$	Crystallographic properties ,Structural, morphological, optical, and electrical properties changes	44

14.	CdTe/CdS thin film with $CdCl_2$ treatment & ITO (Indium tin oxide) coated on both side	Close space sublimation and RF magnetron sputtering	430°C for 30 mins	Bi facial cell is produce which transmit from both sides	45
15.	CdTe/CdS solar cell with O_2 gas in CSS Chamber and $CdCl_2$ treatment	Rf magnetron sputtering, Close-space sublimation (CSS), thermal evaporation, etching	400°C for 30 min	Introduction of O enhanced the concentration of O and Cl in the cell. Also increases the efficiency of cell from 11.5% to 14%	46
16.	Scratch free water white glass substrate with $Hg_xCd_{1-x}Te$ coating	Two-source thermal evaporation		High quality MCT thin film can be produced by two source thermal evaporation and can serve as a very good absorber layer in thin film solar cell	47
17.	7059 corning glasses and ITO coated glass substrates with Cd-rich CdTe coating	Dip – coating and spin coating	Different baking temperature under atmospheric pressure (>180°C)	Prepare by cost effective technique and the film has photocurrent response that can be used in photovoltaic devices	48
18.	Thin film CdTe cell with reducing CdTe layer	Magnetron sputtering	390°C for 30mins	Average efficiency of greater than 12% is measured for as 1µm thin film. Further reduction of thickness cause gradual decrease in efficiency	49

	and $CdCl_2$ treatment				
19.	CdTe/CdS heterojunction solar cell with $MgCl_2$ coating	Rf magnetron sputtering, Close space sublimation (CSS) Dip- coating, thermal evaporation techniques	430°C for 30 mins for solution phase And 430°C for 40 mins for vapour phase of $MgCl_2$	These results demonstrate that $MgCl_2$ can be used as a direct for $CdCl_2$ in the activation step and also it is capable of reducing the cost of CdTe solar-cell production.	50
20.	CdTe/CdS heterojunction solar cell with NH_4Cl	Rf magnetron sputtering, Close-space sublimation (CSS) Dip-coating, thermal evaporation techniques	430°C for 40mins	NH_4Cl was coated on CdTe as the replacement of $CdCl_2$. It was low cost and non- cancer caused material attaining efficiency11.54% which was slight low than $CdCl_2$. However, VOC values was 832 mV were achieved, which shows it can become a good replacement for $CdCl_2$.	51
21	Comparison of different Chloride treatments on CdTe solar cells($CdCl_2$, NH_4Cl, $MgCl_2$, NaCl, KCl, $MnCl_2$)	----------------	-----------------	Comparison between XRD pattern, electrical and optical properties of CdTe solar cells after different chloride treatments.	52

22	$SrCl_2$ under hydraulic press	Full-potential linear augmented plane-wave method plus local orbitals (FP-APW+lo).	------------------	The $SrCl_2$ has direct gap material with EVGGA and an indirect gap (X-Γ) material by using the GGA. the spin-orbit coupling does not effects the electronic and optical properties	53

CHAPTER 3

Experimental Techniques

3.1 Synthesis

Cadmium Telluride powder (99.99% pure) by sigma, $SrCl_2$ of VWR (Product # 28321.268) and methanol of VWR are used in this work. The corning glass substrate was cleaned in ultrasonic bath for 5 mins and dried out by N_2. After that, CdTe was coated on this substrate by Closed Space Sublimation (CSS) technique.

The second material $SrCl_2$ was obtained from strontium chloride hexahydrate $SrCl_2.6H_2O$, we could not obtained in anhydrous form. $SrCl_2.6H_2O$ was heated on high temperature to get anhydrous form of strontium chloride. After making anhydrous milling method was used to get powder form of strontium chloride.

The deposition techniques used in this work are as follow:

- Close Space Sublimation
- Spin Coating

3.2.1 Close Space Sublimation

Close space sublimation is extensively utilized as deposition technique for CdTe, CdS and for other similar semiconductors [54, 55, 56, 57 and 58]. CSS is fascinating method having many benefits. It can provide high deposition rate, large grain size thin film and can be simply rescaled for fabricating purposes. CdTe formed by CSS process at high temperature produced large size grains as compared to the other deposition techniques like CVD or PVD [59]. Taking care in selecting source i.e. it effects the synthesis parameters like deposition rate [60]. The close space sublimation (CSS) method used smaller distance between substrate and source usually less than 1mm.

The CSS method is established in a quartz chamber that is closed. The vacuum is created or the gas is filled up in the chamber. For example, the deposition of CSS-CdTe and CSS-CdS is ambient with O_2 [61]. CdS films that produced in presence of O_2 showed highly efficient devices than the devices fabricated in the presence of inert gases. The main components of reactor are substrate and quartz spacers. The substrate is at a higher place and source is placed at bottom. These components are confined by two blocks of graphite respectively. Thermocouple is place on each graphite blocks to supervise the temperature of substrate and source. Temperature difference is created between source and substrate which allows diffusion insured transport process. Graphite blocks can be heated up by outside lamps which then further transmitted to origin and substrate. Source and Substrate were also heated by resistance heating provided by electric current using graphite blocks as resistances. Both methods can be used together. In CSS system, the main factors affecting deposition rates are the origin and substrate temperature, the spacing, gas and pressure.

Procedure

The diagram of CSS system is shown in below Figure, 99.99% pure cadmium telluride powder was used to prepare thin films on microscopic corning glass substrate. Halogen lamp (1000W) was used to heat source material placed in graphite boat connected with K-type thermocouple for monitoring temperature. The distance between source and substrate was fixed at 5mm. Substrate was heated by halogen lamp (500W) and connected by thermocouple to monitor temperature. Source and substrate temperatures were at 400°C and 300°C respectively with vacuum up to 10^{-3} mbar created by rotary pump. Each film required 5 min for deposit. Open the chamber when temperature reached below 100°C. The films were prepared at thin film technology lab of COMSATS, Islamabad.

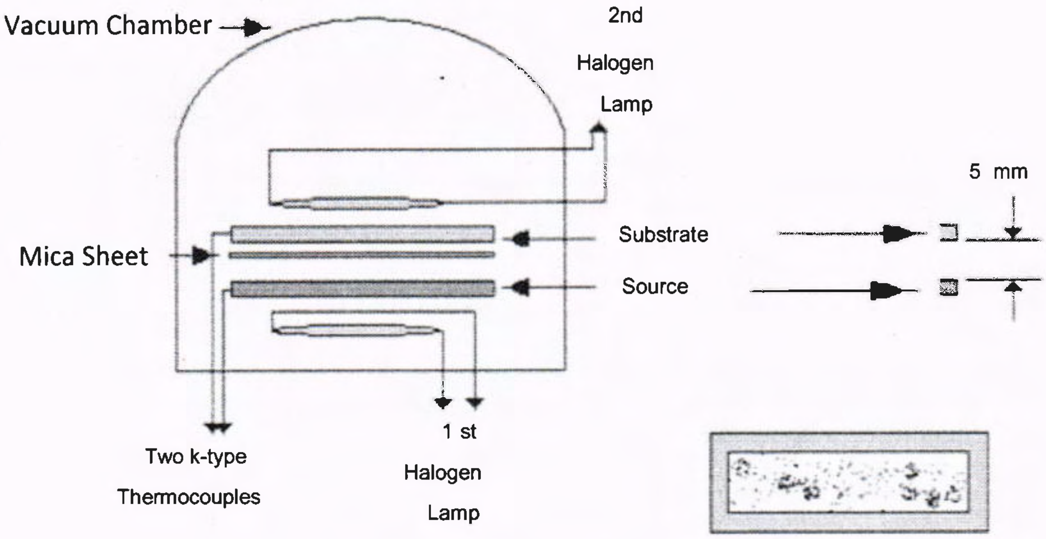


Figure 3. 1 Schematic diagram of CSS

3.2.2 Spin Coating

Introduction

There are number of methods for film deposition, such as wet chemical methods [62,63], physical vapor deposition [64,65], molecular beam epitaxy [66], sputtering [68], pulsed laser deposition [67], spin coating [72], flux method [69], electrospinning [70,71] and even out top-down method by etching [72] etc.

Relatively, spin coating method is a fascinating way for thin film deposition due to the properties: cheap, less hazardous, and easy to rescale [73], can deposit at comparatively low temperature, suitable for organic wafers. The morphologies and properties of final product can be efficiently modified by different parameters, i.e. spin time of spin coater, spin speed, fume exhaust, acceleration of spin coater, etc. [74]. For nonstructural growth of II-VI semiconductors, spin coting has become very dominant and handy technique. Deposition control and multi-layer growth are the two dominant factors that makes spin coting as powerful tool for growth pf nanostructures which improve the properties and morphologies of the developed films.

Spin coating has numerous benefits in coating processes. The main benefits are that thickness of films can simply alters by varying spin speed, or viscosity of photoresist shown by the figure 3.3. Another benefit is the capability of the film to become more uniform as thickness decrease, this uniformity remain till end. It is a cheap and fast depositing method.

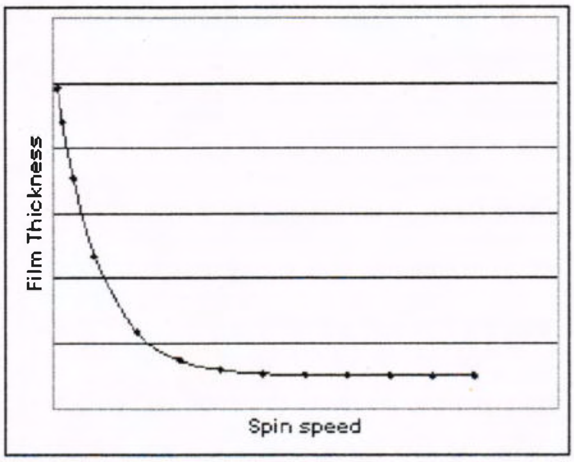


Figure 3. 2 Thickness vs spin speed graph [75]

The relation between the thickness and angular velocity is given below in eq. 3.1.

$$t \propto \frac{1}{\sqrt{\omega}} \qquad (3.1)$$

Instead of remarkable benefits, spin coating have little weaknesses also that are countable as coating material price and substrate size increases. Increase in size produce difficulties in spinning of substrate at high rate which decreases material efficiency. Typically, only 2-5% of material was layered on substrate, whereas the 95-98% residual material is lobbed off in the chunk of spin coater and wasted [76]. Still, spin coating is very simple, cheap and less harmful and can provide tremendous results when properly used.

The spin coating has several key stages: including fluid dispense, stable fluid out flow, spin-up and the last one evaporation dominated drying [77]. A number of factors implied in the spinning procedure are: solution viscosity, solution concentration (c), final spin speed (w), spin time, final film thickness, dispense volume, etc. Using different limitations radius of spreading and the film thickness are measured [78]. Two main independent factors are responsible for thin film formation which are spin speed and viscosity as shown in Figure 3.4. The film thickness simply attained by spin coating is 1nm–200 micrometers [79–80]. The collective flaws in spin coating are as follow:

Comets, Striations, Chuck marks, Environmental sensitivity, Substrate edge effects.

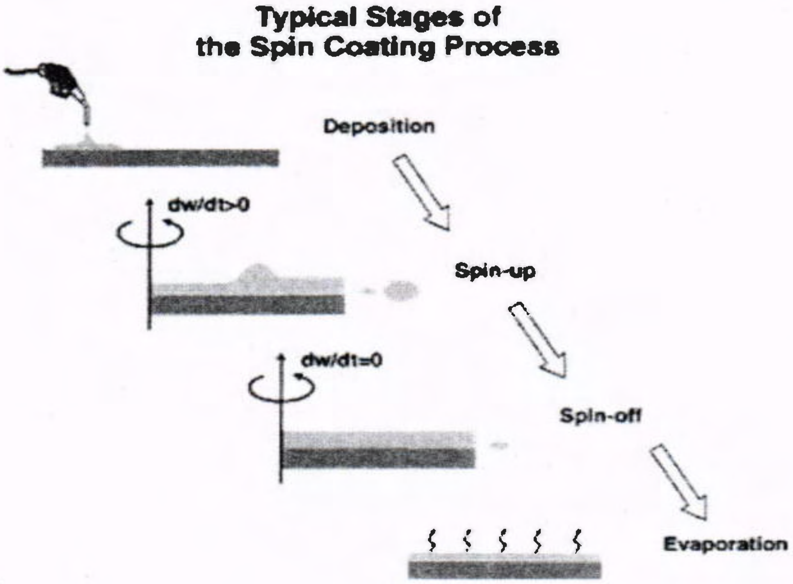


Figure 3. 3 Fundamental steps of spin coating method

Experiment

Thin film was produced on the substrate CdTe by spin coating method. VTC compact vacuum chuck spin coaters (VCT 100) was used for this purpose. It can be rotated from 50 rmp to 8000 rmp. The solution was made with $SrCl_2$ + 10% methanol. The condition used for making thin films are as follow.

Table3. 1 Spin Coating parameters used for coating $SrCl_2$

Sample No.	Molarity (M)	Weight Of $SrCl_2$	T 1 (s)	SPD1 (rpm)	T2 (s)	SPD2 (rpm)
As-deposited CdTe	-------------		---------	-----------	---------	-----------
S1	0.8 m	2.54 g	30	15	40	25
S2	1 m	3.2 g	30	15	40	25
S3	1.2 m	3.8 g	30	15	40	25
S4	1.5 m	4.8 g	30	15	40	25

T1: The "T1" is the time for first spinning stage

SPD1: The "SPD1" is the rotating speed for first spinning stage.

T2: The "T2" is the time for 2nd spinning stage

SPD2: The "SPD2" is the rotating speed for 2nd spinning stage.

Pump: The "Pump" is use for sucking air in vacuum chunk.

CHAPTER 4

Characterization & Techniques

4.1 XRD Diffraction

X-ray diffraction is a well-known method for specimen characterisation [81, 82], and is one of the most important characterisation technique in materials science. X-rays are electromagnetic radiation with a wavelength ranging from 0.1 Å to 100 Å. This technique allows crystalline structures to be probed at the atomic level. The x-ray diffraction pattern of a material is, therefore, like a fingerprint of the substance and also determines the structure of the material. This could be done by the determination of the lattice parameter, the preferred orientation, dislocation density, hkl parameters residual stress as well as the size of the grains in polycrystalline materials, and also the deformation strain. Each crystalline material has its particular properties. X-ray diffraction pattern which may be used as a fingerprint for its identification. Materials may be identified from diffraction patterns, using databases from the ICDD (International Centre for Diffraction Data). Using such references for known materials, X-ray crystallography provides rapid access to information about the lattice type, interatomic distances and angles between planes.

The diffraction condition is explained by Bragg's law by eq. 4.1.

$$\mathrm{n}\lambda = 2\mathrm{dsin}\Theta \qquad (4.1)$$

where λ is the x-rays wavelength, Θ is the angle between the reflected beam and the diffracted plane, d_{hkl} is the interatomic distance between hkl planes and n is the order of diffraction and is always assumed to be equal to 1. This is shown in the Figure 4.1

Where

$$n\lambda = ABC \qquad (4.2)$$

$$AB = dsin\theta \qquad (4.3)$$

$$n\lambda = 2dsin\theta \qquad (4.4)$$

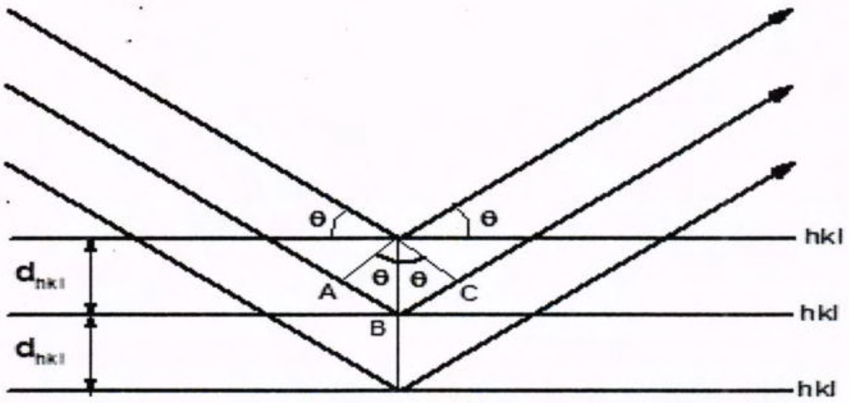


Figure 4. 1 Diffraction of X-rays from atomic plane in a crystal

4.1.1 Thin Film Diffraction

There are several special reasons for using XRD to characterize thin film samples.

I. As the substrate are too thick for the transmission so reflection is used.
II. High angular resolution is required due to low defect densities semiconductor shows sharp peaks.

Primary XRD measurements used on thin film samples are:

Precise lattice constants measurements derived from 2Θ - Θ scans, providing information about the lattice mismatch between film and substrate and indicating the strain & stress

Rocking curve measurements made by doing a Θ scan at a fixed 2Θ angle, whose width is inversely proportionally to the dislocation density in the film and hence, it is used as a gauge of the quality of the film.

Super lattice measurements in multi-layered hetroepitaxial structures (crystalline structures), which manifest as satellite peaks surrounding the main diffraction peak from the film. Film thickness and quality can be deduced from the data.

Glancing incidence x-ray reflectivity

Measurements, are used to find the thickness, roughness, and density of the film. This method does not need crystalline film and works even with amorphous materials

Where, k is a constant valued as 0.9. λ, β, and θ are the X-ray wavelength (=1.5406Å), FWHM and Bragg angle respectively.

The dislocation density (ρ), which signifies the quantity of imperfections in the crystal, equation for dislocation density is given below by eq. 4.4. [84]

$$\rho = \frac{1}{D2} \tag{4.8}$$

Equation for Strain (ε) of the thin film is shown as eq.4.5. [84]

$$\epsilon = \frac{\beta}{4\tan\theta} \tag{4.9}$$

4.2 Scanning Electron Microscopy

Scanning electron microscopy is used for study of surface of specimens through image analysis. Secondary electron beam are emitted from the surface when electron beam falls on the surface of the specimen. SEM is used in different areas i.e. medicine, electronics, energy, biotechnology for analysing progress of nanostructured material, processes and phenomena on micro and nanoscale [85–88]. Commonly, analysis can be done by secondary electrons excited by electron beam from atoms. On a plane surface, the cloud of secondary electrons is mostly contained by the sample, but on a tilted surface, the plume is partially exposed and more electrons are emitted. An image of surface morphology of sample is formed by scanning the sample and detecting these secondary electrons.

Usually, there are two kinds of electron microscopes, transmission electron microscope (TEM) and scanning electron microscope (SEM). TEM measures change in electron beam as it pass through the sample. SEM scans the surface of the specimen by falling electron beams on the surface. SEM provides the information about the surface terrain internal structure of specimen, composition and electrical conductivity by interacting electronic beams with the specimen's atoms and observe only the surface [89].

In SEM, the resultant signals was the results of electron beam interact with the surface of specimen, contains secondary electrons, back-scattered electrons (BSE), characteristic X-rays, light, specimen current and transmitted electrons [89]. By detection of secondary electron, SEM can produce vivid images of a sample surface (secondary electron image, or SEI), with superior resolution about 1 to 5 nm. SEM has considerable depth of field than TEM when relative narrow beam of electron used. Complicated surface morphology can be examined by using three dimensional appearance of SEM. Characteristic X-rays are emitted as the electron beam removes an inner shell electron from the sample, causing a higher energy electron to fill the shell and release energy. These X-rays can be used to classify and quantitively determinate elements in samples. BSE (Back Scattering Electrons) are produced by elastic interactions of beam electrons with nuclei of atoms in the specimen. As heavy atoms (high atomic number) shows strong scattering than lighter atoms, compositional information can be taken out by images with BSE thus the distribution of different elements in sample can be get from BSE images. The brief explanation of SEM is as follow: [90]

I. Vacuum system. Electron beam scatter rapidly after collision with molecules so vacuumed atmosphere required.
II. Electron beam generator. This part generates electron beam which is setup on top of microscope column shown in Figure 4.2.
III. Electron beam manipulation system. The size shape and position of electron beam is control by this part. This part consist of electromagnetic lenses and coil.
IV. Beam specimen interaction system. Interaction of beam of electron with the sample and detection of signals have been done in this section.
V. Detection system. Some different kind of detectors are used in this part having sensitivity on different conditions of emission of particles and energies that happen on specimen.
VI. Signal processing system. Signals are processed in this electronic section and also makes manipulation of image.
VII. Display and recording system. Visualization of electronic signals have done in this signal by using cathode ray tube allows make copy of results in the form of photographic media.

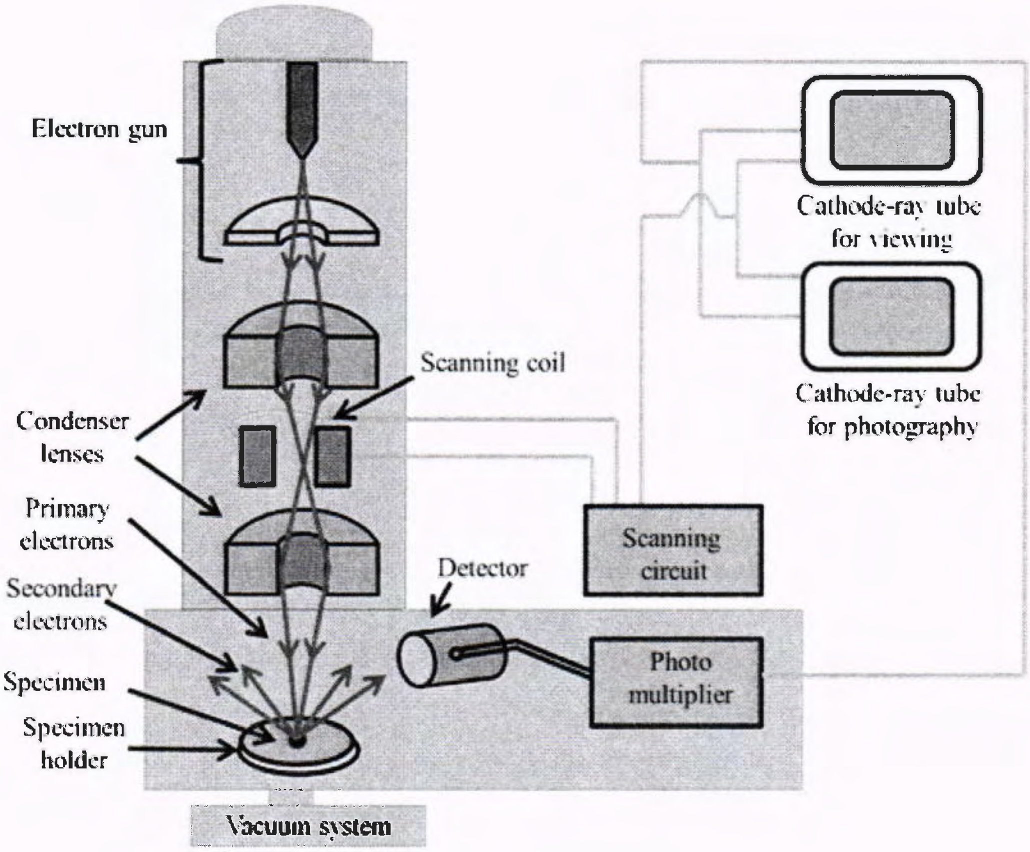


Figure 4. 2 Key Steps of SEM [90]

4.3 Current-Voltage Characteristics

Current-Voltage (I-V) gives the product of voltage and current for photovoltaic cells. When the resistance of cell is zero, it produced maximum current. In I-V measurement, the device response is monitored to a corresponding applied voltage, from 0 volts (short circuit) to the open circuit voltage, with constant AM1.5 (Standard global solar spectrum) illumination. The current measured at zero voltage is the short circuit current I_{sc} (mA) and is often describe in terms of short circuit current density (J_{sc}) expressed as (mA/cm^2) The open circuit voltage (V_{oc}) is measured at zero current. From the I-V curve a power curve can be generated, where (V_{mp}) is the maximum power voltage, maximum power current density (J_{mp}), and maximum power point (MPP). The power lost caused by series and shunt resistance is expressed with fill factor (FF). The ratio between MPP and product of V_{oc} and J_{sc} is defined as fill factor (FF).

Parasitic losses from shunt (R_{sh}) and series (R_s) resistances reduce the FF. Device efficiency (η) is calculated as a ratio of produced power to the power input. Test methods and apparatus are well defined by Davies [91].

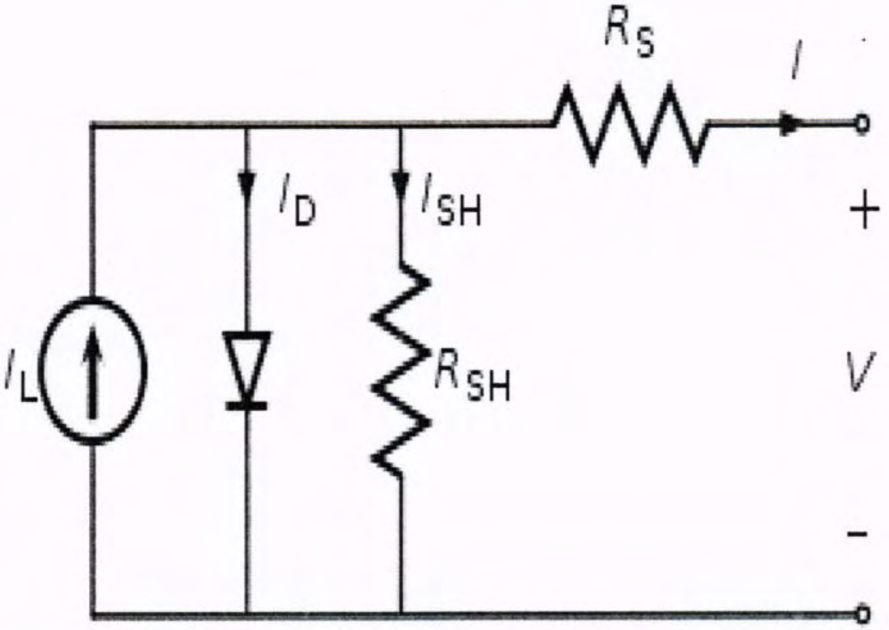


Figure 4. 3 Corresponding circuit of a Photovoltaic cell [92]

The device used for I-V characterization is shown in the Figure 4.4

Figure 4. 4 ASMEC-Electro-Physical Characterization System

4.4 Ellipsometry Studies

Optical measurement techniques are of great importance in characterizing sample since these techniques are normally non-invasive. Ellipsometry is a non-destructive technique and a remarkable evaluating system on nanoscale. Only bleached sensitive planes can be damaged by optical measurements. There are a number of optical instruments presents which relies on transmission or reflection of light through surface like interferometry, reflectometry and ellipsometry. Three kinds of ellipsometry are scattering, transmission and reflection ellipsometry [93]. Physical properties of any optical devise which makes change in polarization state of incident light wave can be measured by ellipsometry. Thickness of very thin films can be measured by high accuracy by ellipsometry up to Å scale or below while calculating thicker films further manipulations are required which are more complex. Other probable applications of ellipsometry are determination of the refractive index, the surface roughness or the uniformity of a sample and more. The formulae used for our work was given below

Band gap was also measured by spectroscopic ellipsometry. The formula used for the band gap measurements was given below by eq. 4.9 [94].

$$\alpha h\nu = A(h\nu - Eg)^{N/2} \tag{4.6}$$

Where A is a constant, hν is photon energy, Eg is optical energy gap, and N relies on the nature of the transition (N = 1 for direct band gap and N =4 for indirect band gap transition).

While

hν (eV) = 1240/nm

The absorption coefficient of $CdTe/SrCl_2$ thin film was measured by the relation given bellow by eq. 4.6 [95].

$$\alpha = \frac{4\pi k}{\lambda} \tag{4.7}$$

Extinction coefficient was measured by the equation given below by eq. 4.7 [95].

$$k = \frac{\alpha\lambda}{4\pi} \tag{4.8}$$

Where 'K' is the extinction coefficient, 'α' is absorption coefficient and 'λ' is wavelength

Refractive index was measured by the following equation by eq. 4.8 [95].

$$\dot{n} = n + ik \tag{4.9}$$

Where **k** is extinction coefficient.

The device used for optical characterization is shown in the figure 4.6.

The relationship between the transmittance (T), absorption (A) and reflectance (R) has been given by eq. 4.10 [95].

$$T + R + A = 1 \tag{4.10}$$

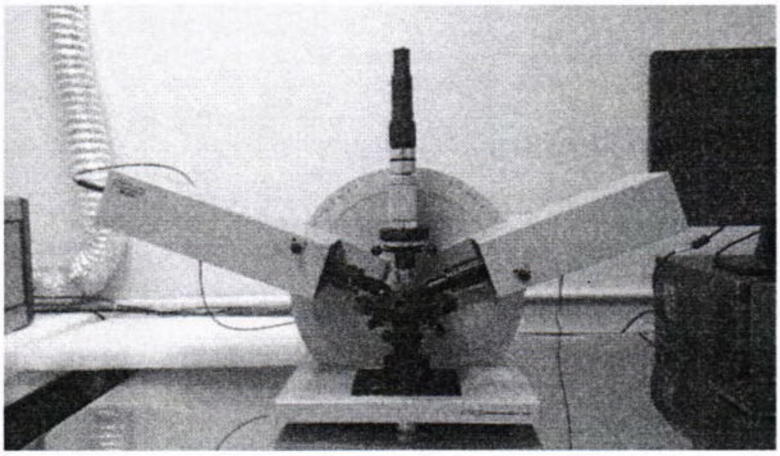


Figure 4. 5 Metrology Grade Spectroscopic Ellipsometer

CHAPTER 5

Results & Discussions

5.1 Structural Analysis

XRD technique has been used for the analysis of crystalline structure analysis of thin film of CdTe coated with $SrCl_2$ with different molarity concentrations. $SrCl_2$ molarity concentrations are 0.8 M, 1.0 M, 1.2 M, and 1.5 M named as S1, S2, S3, and S4 sample respectively are annealed at 200°C in vacuumed conditions on 10^{-3} mbar. The purpose of this coating was to get larger crystallite size and enhance grain boundaries [96, 97] and improve the crystal structure and conductivity of P-CdTe. Fig 5.1, 5.2, 5.3, 5.4, 5.5 represents the XRD pattern of CdTe as-deposited and thin films coated by different concentrations of $SrCl_2$ on different molarities respectively.

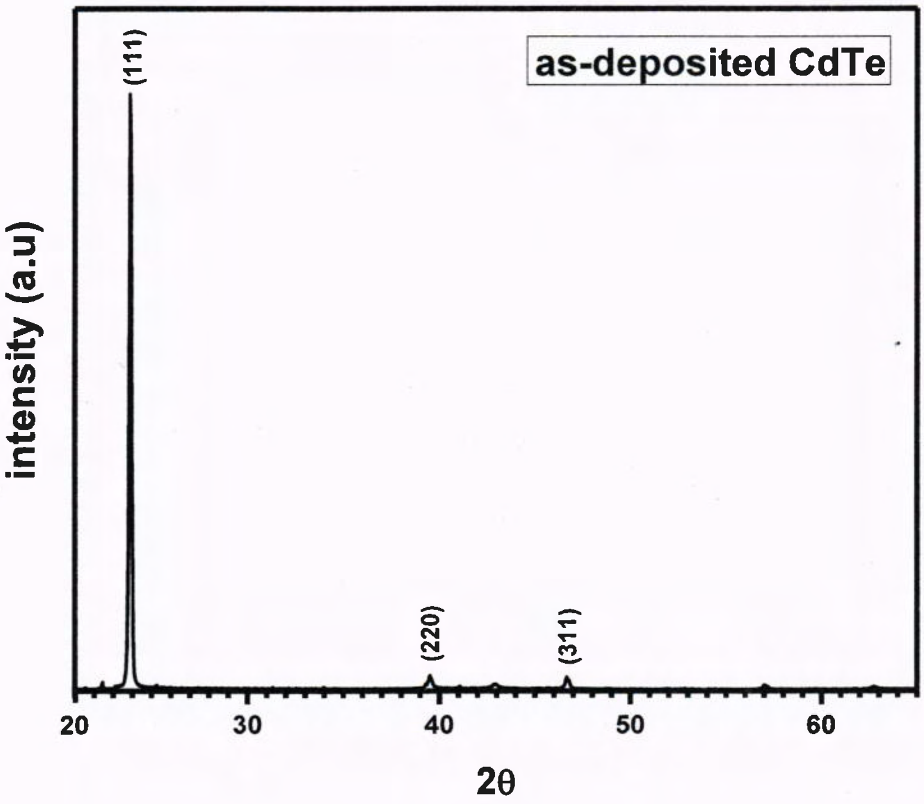


Figure 5.1: XRD spectrum of CdTe as-deposited

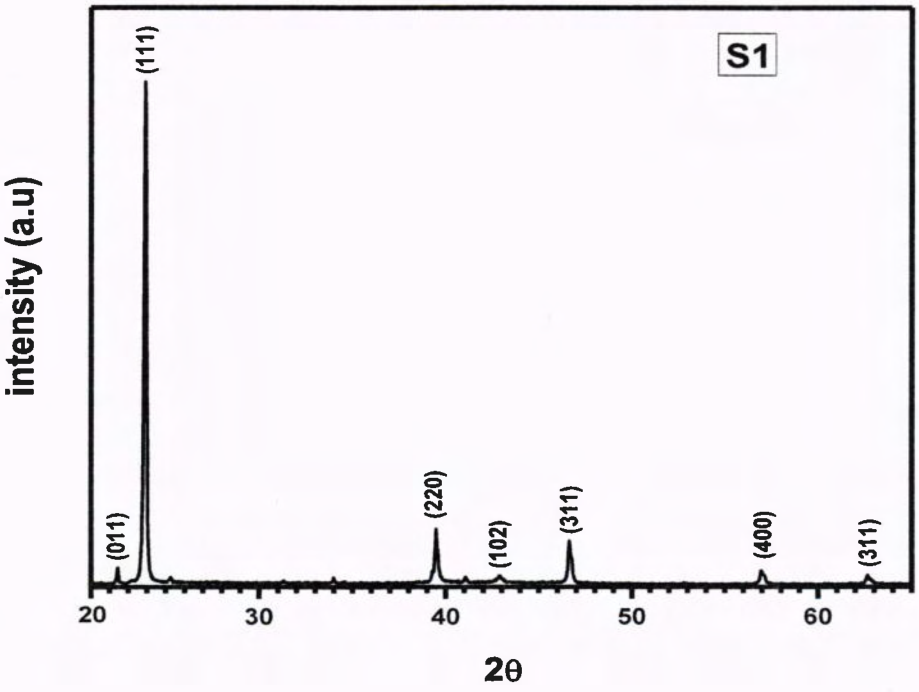


Figure 5.2: XRD spectrum of CdTe thin film, 0.8 M $SrCl_2$ coated.

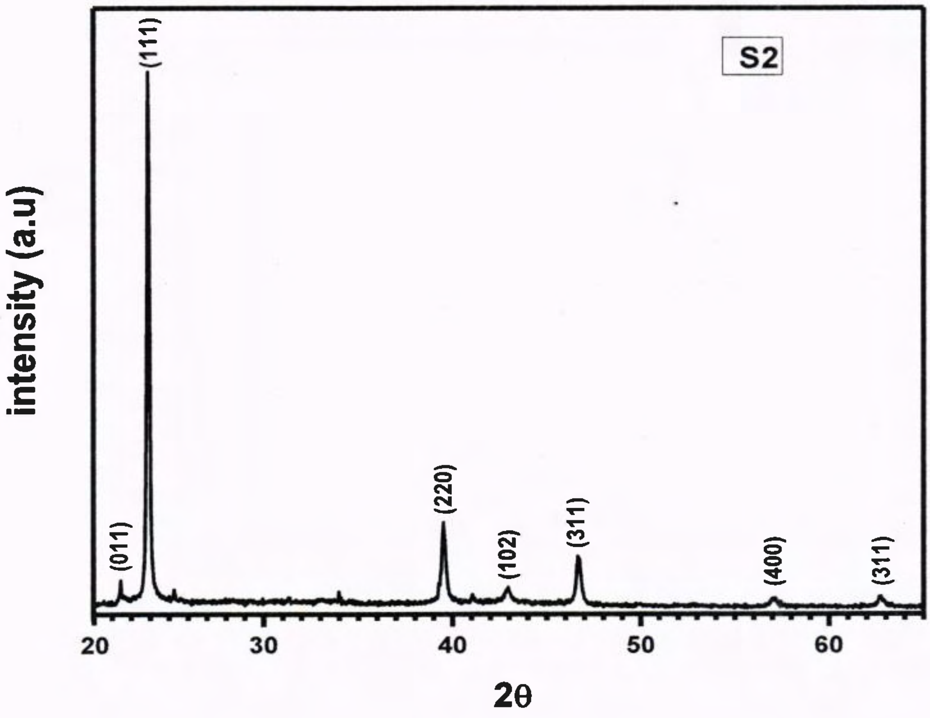


Figure 5.3: XRD spectrum of CdTe thin film, 1.0 M $SrCl_2$ coated

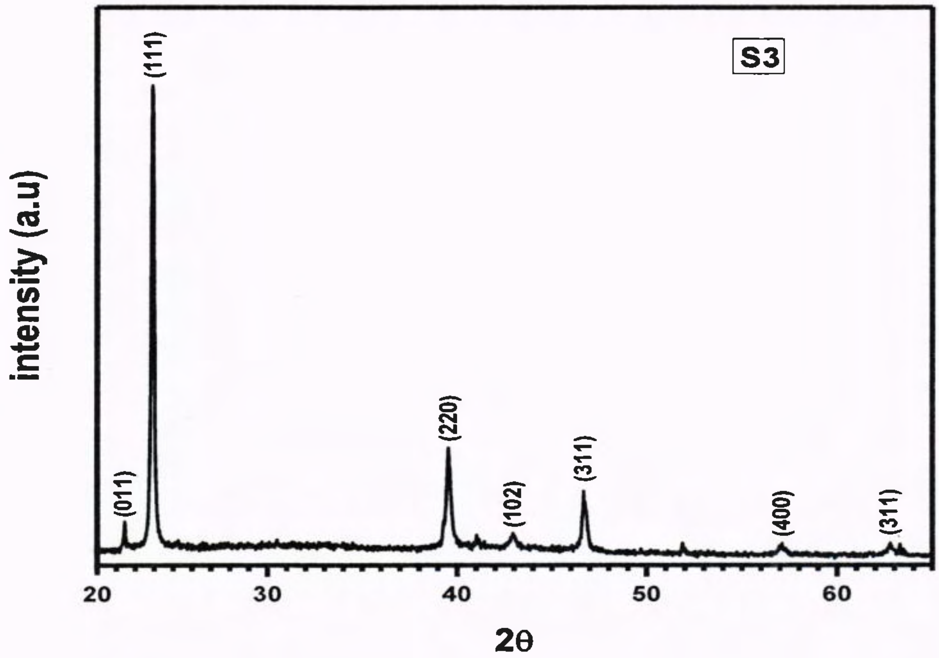


Figure 5.4: XRD spectrum of CdTe thin film, 1.2 M $SrCl_2$ coated

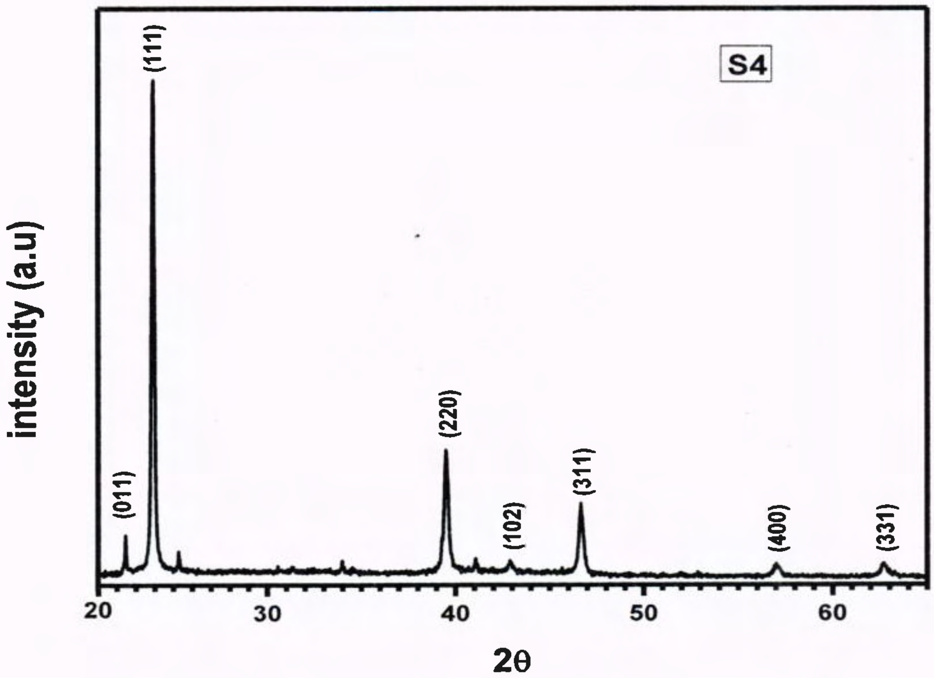


Figure 5.5: XRD spectrum of CdTe thin film, 1.2 M $SrCl_2$ coated

The main peaks are similar in all samples and can be determined by f_{cc} CdTe lattice. This study shows about same lattice constant 6.44Å for all samples, which matched with stated value 6.49Å [98, 99] ASTM Cards 00-010-0207. The strongest reflection in (111) direction in samples specify the preferred orientation. Intensity at (111) decrease with the increase of $SrCl_2$ concentration in samples respectively. Decrease in intensity at (111) directed better crystallinity [100]. At the same time, intensities increases on orientations (220) and (311) with increase in concentration of $SrCl_2$ shows that material loses the preferential orientation along the (111) plane and becomes poly-crystalline [101]. On some other angles peaks tried to grow up (400) and (331) but they had much lower intensities. Peaks of $SrCl_2$ (011) and (102) matched with (ASTM Cards 00-032-1225) were also observed on two different orientations but they also had not sufficient intensities. No momentous change observed in diffraction angles.

The crystallite size was calculated by Scherrer formula given below in eq.5.1

$$D = \frac{0.9\,\lambda}{\beta Cos\theta} \tag{5.1}$$

λ, β and Θ are wavelength, full width at half maximum and diffraction angle respectively are used. [102, 103]. Dislocation density is calculated by $1/D^2$ [104]. Lattice strain ϵ was calculated by formula in eq.5.2 [105].

$$\epsilon = \frac{\beta}{4tan\theta} \tag{5.2}$$

The crystalline size of deposited CdTe thin film was 20.38 nm, after $SrCl_2$ treatment crystalline size increases up to 25.7nm with increase in $SrCl_2$ concentration and decrease in dislocation density was observed which may be attributed to enhancement of crystal structure [106]. Diffraction angles with peaks, FWHM, crystalline size, miller indices, d-spacing, lattice constant, dislocation density and lattice strain of as deposited CdTe and $SrCl_2$ coated samples is shown in the Table 5.1.

Table 5. 1 XRD parameters of all CdTe Samples: as-deposited and $SrCl_2$ coated samples

Samples Names	$SrCl_2$ Molarity (mole)	Miller indices (hkl)	FWHM (deg)	Peak Position (deg)	Grain Size (nm)	d-spacing (Å)	Lattice Constant (Å)	Dislocation Density	Lattice Strain
As-deposited	———	111	0.398	23.88	20.38	3.72	6.44	2.4E-3	8.1E-3
		220	0.173	39.50	49.5	2.28	4.56	4.1E-4	2.1E-3
		311	0.21	46.66	40.77	1.944	6.45	6E-4	2.1E-3
S1.	0.8 M	111	0.377	23.92	21.32	3.715	6.43	2.2E-3	7.7E-3
		220	0.328	39.48	25.67	2.265	4.53	1.52E-3	3.9E-3
		311	0.311	46.62	27.72	1.946	6.45	1.3E-3	3.1E-3
S2.	1.0 M	111	0.364	23.88	22.36	3.719	6.44	2E-3	7.4E-3
		220	0.37	39.52	22.72	2.28	4.56	1.9E-3	4.5E-3
		311	0.441	46.66	26.52	1.94	6.44	2.6E-3	1.8E-3
S3.	1.2 M	111	0.324	23.92	24.75	3.72	6.44	1.6E-3	6.7E-3
		220	0.447	39.54	18.99	2.28	4.56	2.8E-3	5.4E-3
		311	0.356	46.68	24.32	1.944	6.43	1.7E-3	3.6E-3
S4.	1.5 M	111	0.31	23.91	25.7	3.72	6.44	1.5E-3	6.4E-3
		220	0.44	39.48	18.25	2.264	4.53	3E-3	5.3E-3
		311	0.44	46.66	19.8	1.944	6.5	2.6E-3	4.4E-3

5.2 Surface Morphology of CdTe Layer

The surface morphology of CdTe and $SrCl_2$ coated thin films was observed using scanning electron microscopy (SEM, JEOL, Model JSM 5910). Recrystallization was observed in $SrCl_2$ treated samples, rearrangement was observed in grain size, grain boundaries and shape. However, wider grain boundary regions are not preferred as they affect the conduction through the grain boundaries as well as they may also cause shunt-path formation causing a weak p-n junction [107]. For high efficiency and stable cells with large grains and compact CdTe is required. Grain size and grain boundaries enhanced with increase in concentration of $SrCl_2$, as shown in the Figure 5.6, 5.7 and 5.8. $SrCl_2$. Grain with small size merged together and larger grains splits in to smaller grains and reoriented themselves effecting whole structure [108, 96]. SEM images also indicate the rough and overlapping of grains in as-deposited sample and decrease in roughness of CdTe layer by increasing concentration of $SrCl_2$. These results are matched with XRD results. Widening of grain boundaries was also observed in samples. Most wide grain boundaries was observed in S2.

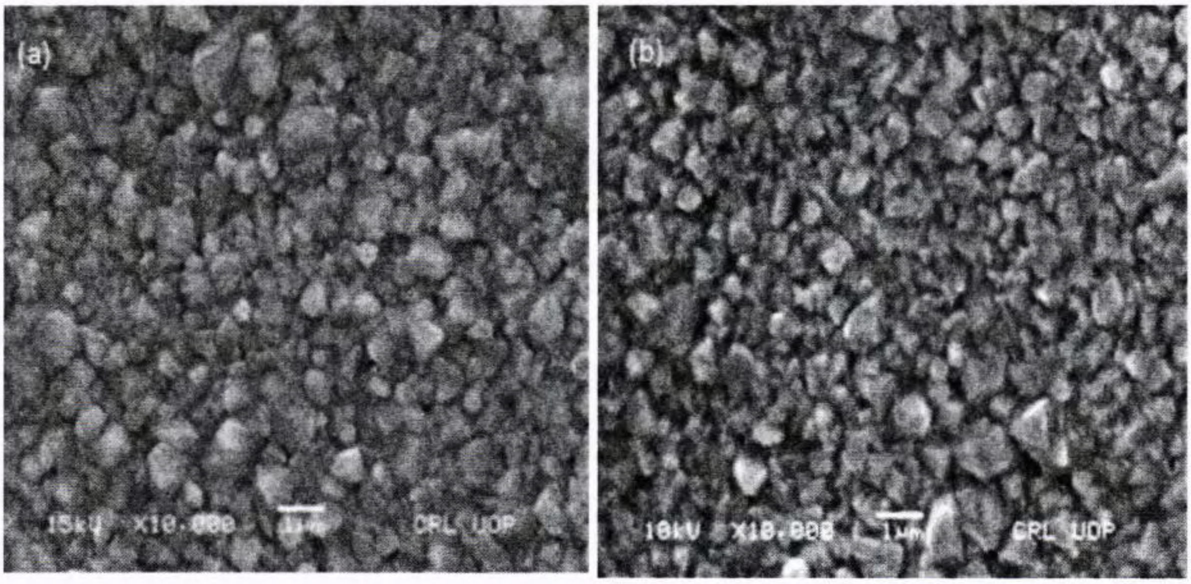


Figure 5. 6 SEM image of as-deposited CdTe film (a), 0.8 M $SrCl_2$ coated CdTe film (b)

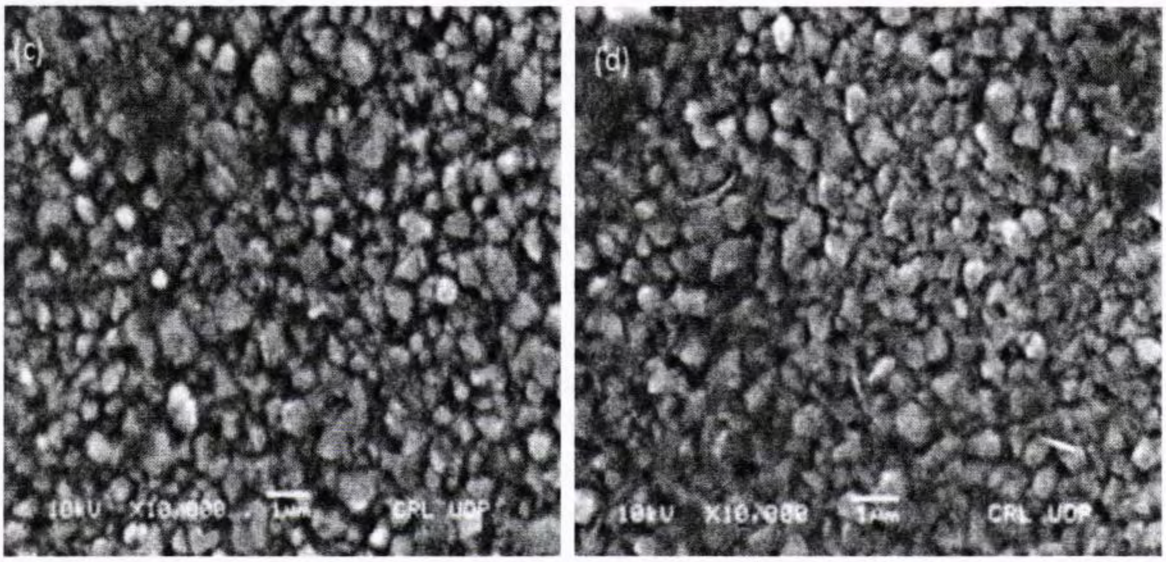


Figure 5. 7 SEM images: 1.0 M $SrCl_2$ coated CdTe thin film (c), 1.2 M $SrCl_2$ coated CdTe thin film (d)

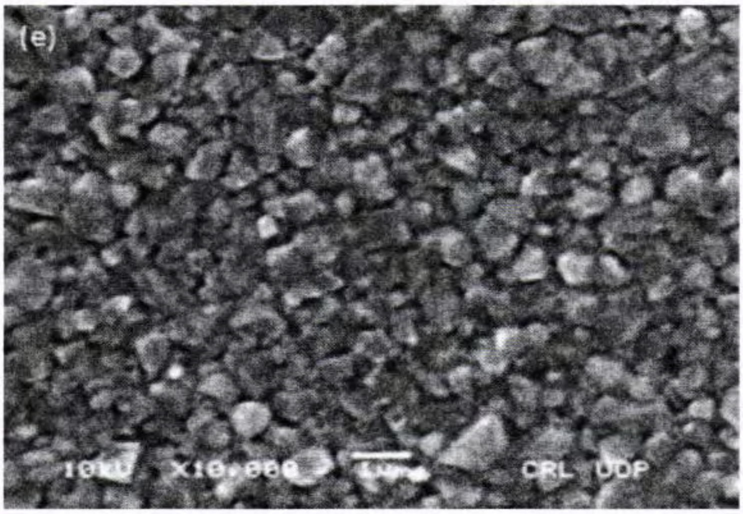


Figure 5. 8 SEM images: 1.5 M $SrCl_2$ coated CdTe thin film

5.3 Current- Voltage Characteristics (I-V)

The current-voltage characteristic were studied with CdTe thin film coated with $SrCl_2$ of different molarities of 0.8M, 1.0M, 1.2M, 1.5M and 1.8M annealed at 200°c. The heating chamber pressure was 10^{-3} mbar. This device is tested up to 5 V. CdTe was used as positively biased as compared to $SrCl_2$. This devise was tested up to 5V as bias-voltage, and I - V was tested in dark as well as in luminous conditions (1.8E5 lux light). The comparison for each concentration between dark current **'I_D'** and photo current **'I_p'** was shown in the Figures given below.

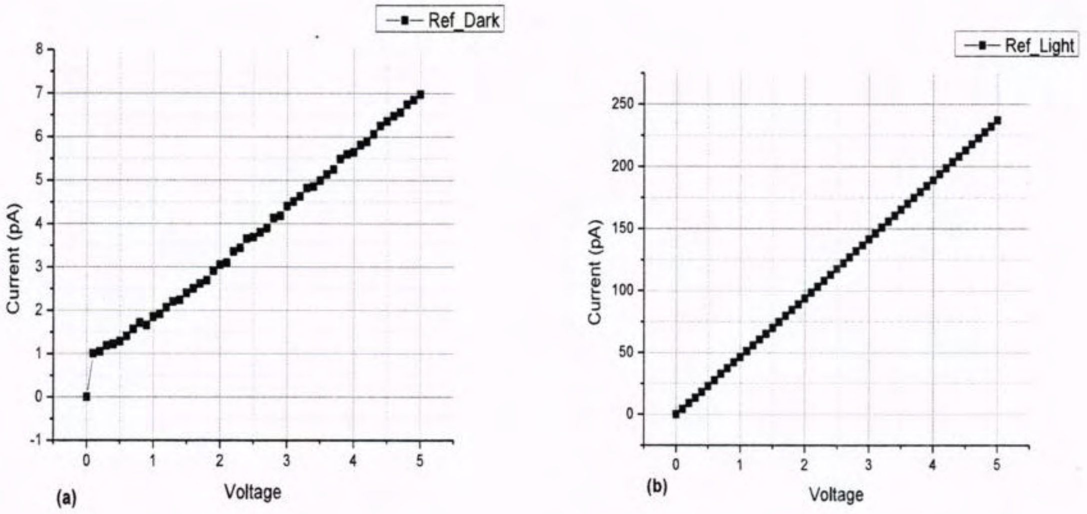


Figure 5. 9 (I-V) response of CdTe thin film: as-deposited, (a) in dark (b) in light

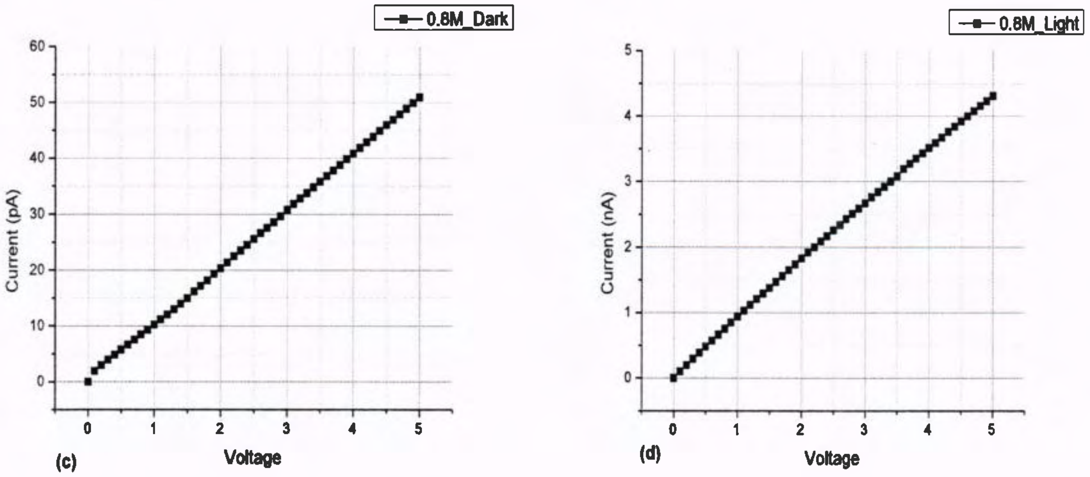


Figure 5. 10 (I-V) response of CdTe thin film: S1 sample (c) in dark (d) in light

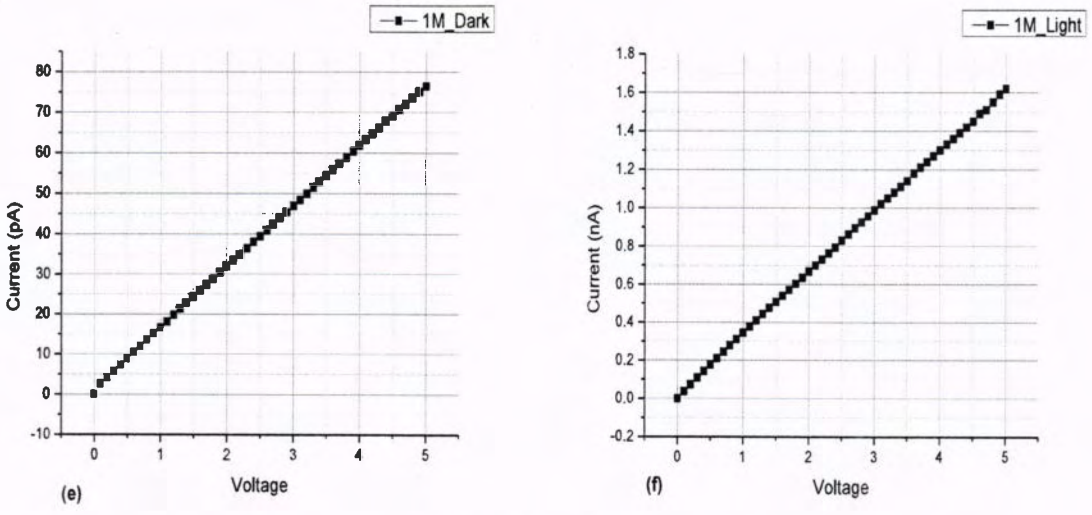


Figure 5. 11 (I-V) response of CdTe thin film: S2 sample (e) in dark (f) in light

In Figure 5.9 CdTe thin film layer showed dark current '**I_D**' only 7pA, after luminous effect photo current '**I_P**' increased up to 237pA. In Figure 5.10 CdTe thin film was coated with 0.8M of $SrCl_2$ was shown. After coating dark current increases up to 51pA and photo current increased up to 4.31nA. In Figure 5.11 CdTe layer was coated with 1M of $SrCl_2$, it was shown that dark current increased up to 76.5pA, while the photo current cutback to 1.62nA. This reduction was may be due to large grain boundaries or due to crystal defects.

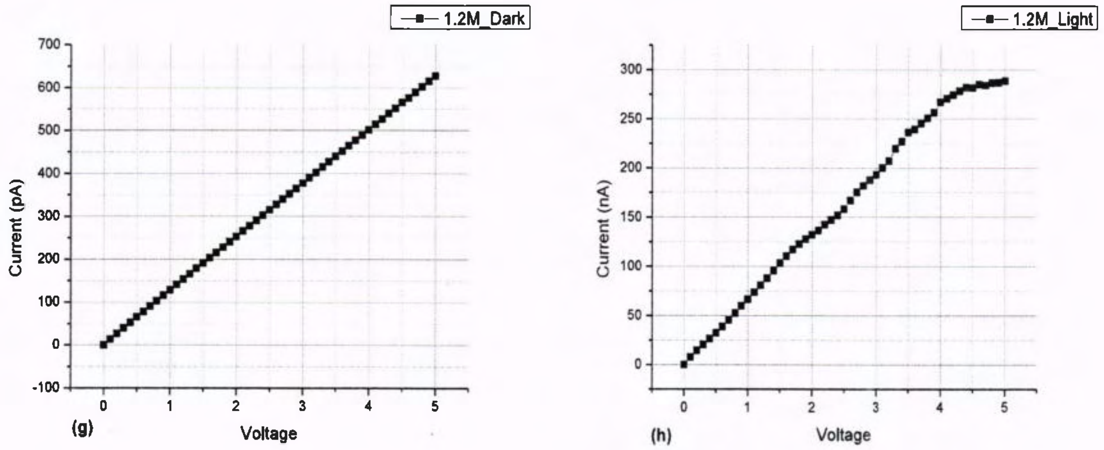


Figure 5. 12 (I-V) response of CdTe thin film: S3 sample (g) in dark (h) in light

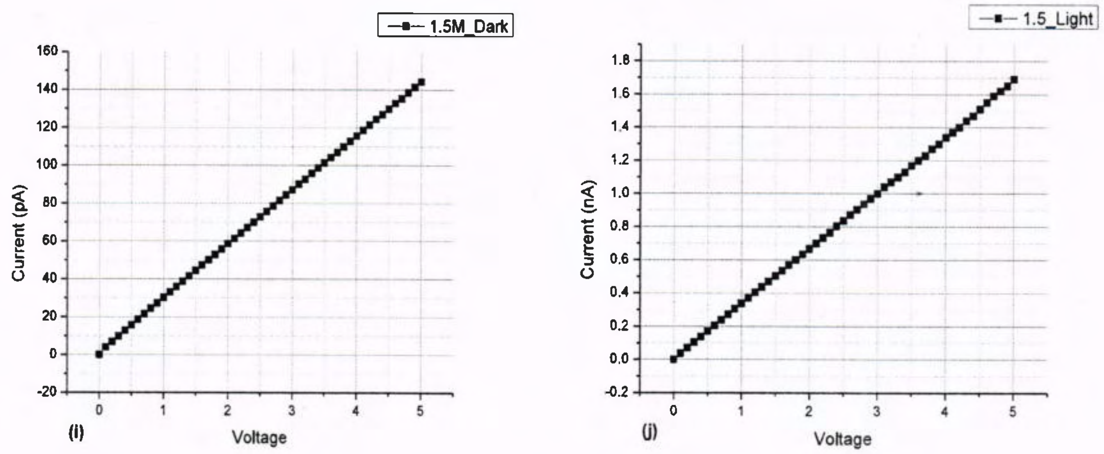


Figure 5. 13 (I-V) response of CdTe thin film: S4 sample (i) in dark (j) in light

In Figure 5.12 CdTe layer was coated with 1.2 M of $SrCl_2$, a remarkable change in dark and photo current was measured. Dark current increased up to 627pA and 288.5nA photo current was measured which was the highest photo current with respect to all samples. This was may be due to better crystallinity, larger grain size and compact structure of CdTe.

In Figure 5.13 CdTe layer was coated with 1.5 M of $SrCl_2$ was coated. In this sample, dark and photo current both reduced to 160pA and 1.7nA respectively. The deposition technique and post-deposition annealing conditions also matters for grain size and conductivity of thin films. May be better deposition technique and conditions increases conductivity.

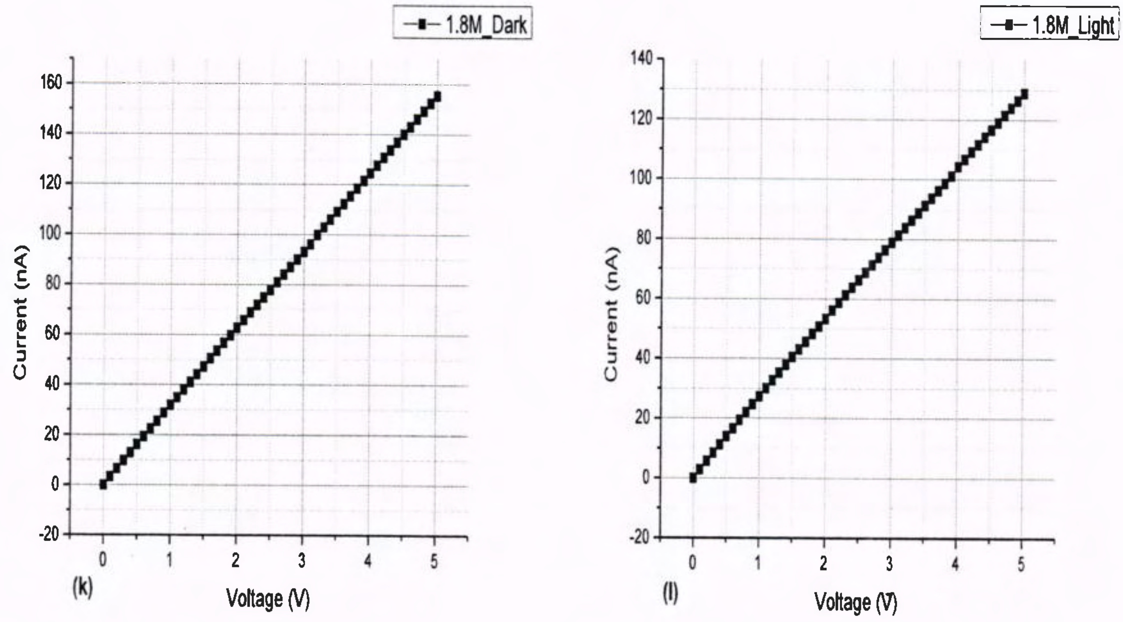


Figure 5. 14 (I-V) response of CdTe thin film: S5 sample (k) in dark (l) in light

For the confirmation of conductive behaviour, one more sample of 1.8M of $SrCl_2$ was tested, which showed again increase in dark current about 155.5nA recorded, but again photo current cutback to 130nA with respect to dark current. However, current may be reduced due to crystals defects or may be some clause left in deposition and annealing conditions as shown in the Figure 5.14.

Overall resonance of these I-V outcomes was that, CdTe shows much better photoconductive character after coating. $SrCl_2$ enhancing conductivity ability of CdTe. Reduction in bandgap indicates enhancement of transmission which is also one of the factor that increases current through thin films after coating $SrCl_2$ by increasing the efficiency of conversional energy. Although, not so much current was produced but a very small amount of $SrCl_2$ was used. May be photo current increased with increase in thickness of thin film. The current-voltage showed linear increase in all samples which indicates that current increased exponentially with increase in voltage [109]. The comparison between all dark I-V responses and light I-V responses is also shown in the Figure 5.15 and 5.16.

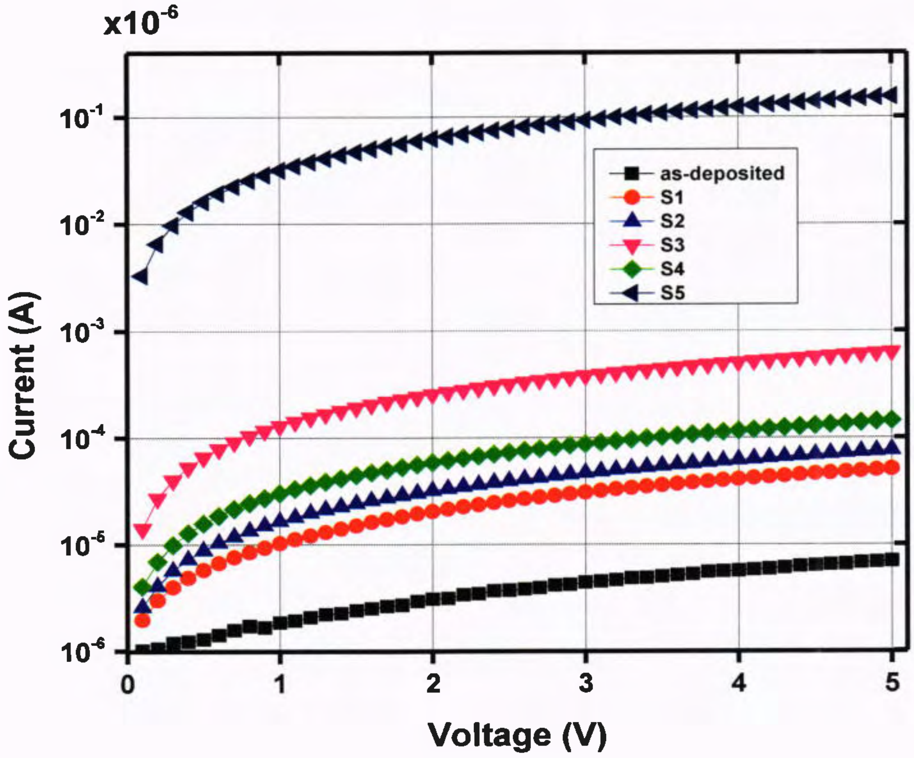


Figure 5. 15 Comparison of dark currents (Id) of CdTe as deposited and $SrCl_2$ coated samples

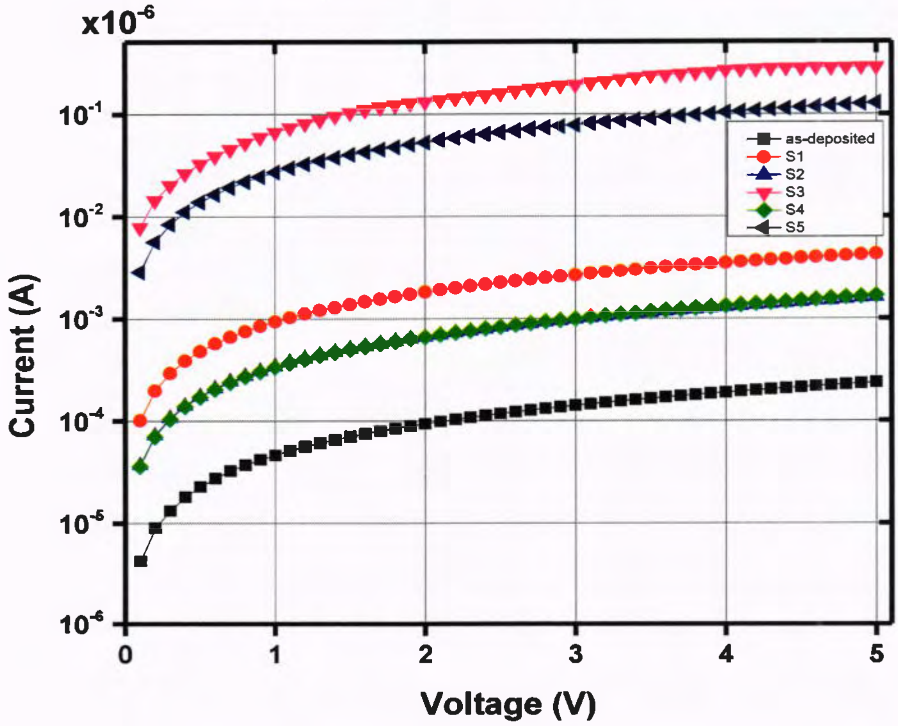


Figure 5. 16 Comparison of light currents (Ip) of CdTe as deposited and $SrCl_2$ coated samples

5.4 Optical Measurements

Optical measurements was carried out by spectroscopy ellipsometry (SE). This is a non-destructive technique for analysis of optical properties of thin films. In this work, this technique was used for determination of the thickness, refractive index, extinction coefficient, absorption and band gap. The model used for this purpose is Forouhi-Bloomer model (FB) and error was measured by mean square error (MSE). The formula of (MSE) is

$$MSE = \frac{1}{2N-M}\sum_{i=1}^{N}\left[\left(\frac{\Psi_i^{cal}-\Psi_i^{exp}}{\sigma\Psi_i^{exp}}\right)^2 + \left(\frac{\Delta_i^{cal}-\Delta_i^{exp}}{\sigma\Delta_i^{exp}}\right)^2\right] \tag{5.3}$$

Where

N is the number of data points in the spectra

M is the number of variable parameters in the model

σ is the standard deviations on the experimental data points.

Ψ^{exp} and Δ^{exp} are the measured values of Ψ and Δ while Ψ^{cal} and Δ^{cal} are the corresponding calculated values

5.4.1 Thin film thickness

The thickness of coated $SrCl_2$ with different molarity concentration on CdTe thin film is given bellow.

Table 5. 2 Thickness of $SrCl_2$ coated on CdTe thin films

Samples Names	$SrCl_2$ Concentration	Thickness of $SrCl_2$(nm)	Error in thickness (%)
As-deposited	————	227.00	±1.50
S1	**0.8 M**	38.86	±2.02
S2	**1 M**	47.45	±0.96
S3	**1.2 M**	50.90	±1.20
S4	**1.5 M**	54.11	±1.42

5.4.2 Reflectance Measurement

The optical properties were analysed for wavelength range 350 to 800nm using ellipsometer at room temperature. Reflectance measurements were also carried out by ellipsometry technique. The measurements were carried out on CdTe thin films with varying $SrCl_2$ concentrations. We observed that by increasing $SrCl_2$ concentration the reflectance decreases. The relationship between the transmittance (T), absorption (A) and reflectance (R) is given by eq.5.3 [110].

$$T + R + A = 1 \qquad (5.4)$$

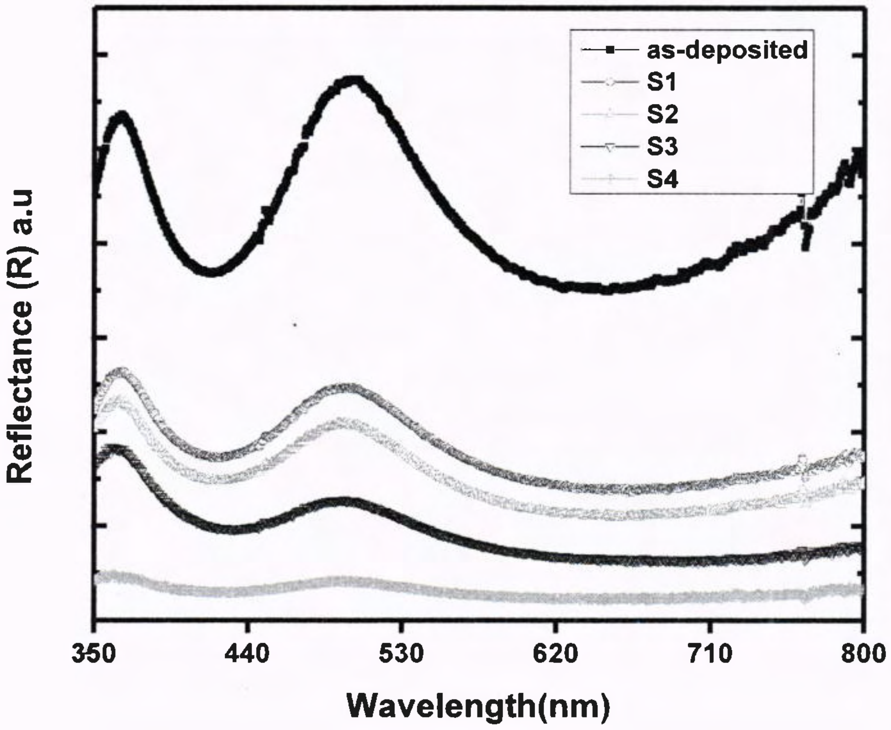


Figure 5. 17 Comparing reflectance of CdTe as deposited and coated samples

5.4.3 Extinction Coefficient

The extinction coefficient explains the energy dissipation in the thin film and depends on wavelength. The light waves loses energy exponentially in thin film which was absorbed by thin film. This energy dissipation is shown by Beer's Law

$$I(z) = I(0)e^{-i\alpha z} \qquad (5.5)$$

Extinction coefficient is associated with absorption coefficient, decrease in extinction coefficient causes increase in absorption. Extinction coefficient was measured by the equation 5.5 given above [110, 111].

$$\alpha = \frac{4\pi k}{\lambda} \tag{5.6}$$

Extinction coefficient 'k' was plotted against the wavelength and a significant decrease was observed in extinction coefficient with respect to the CdTe as-deposited sample. The extinction coefficient of as-deposited CdTe thin film is found reduced after $SrCl_2$ coating, which was further decreased by the increasing content of coating material. Maximum change was observed in S3 that means sample S3 shows maximum transmission and absorb maximum photon energy w.r.t other samples.

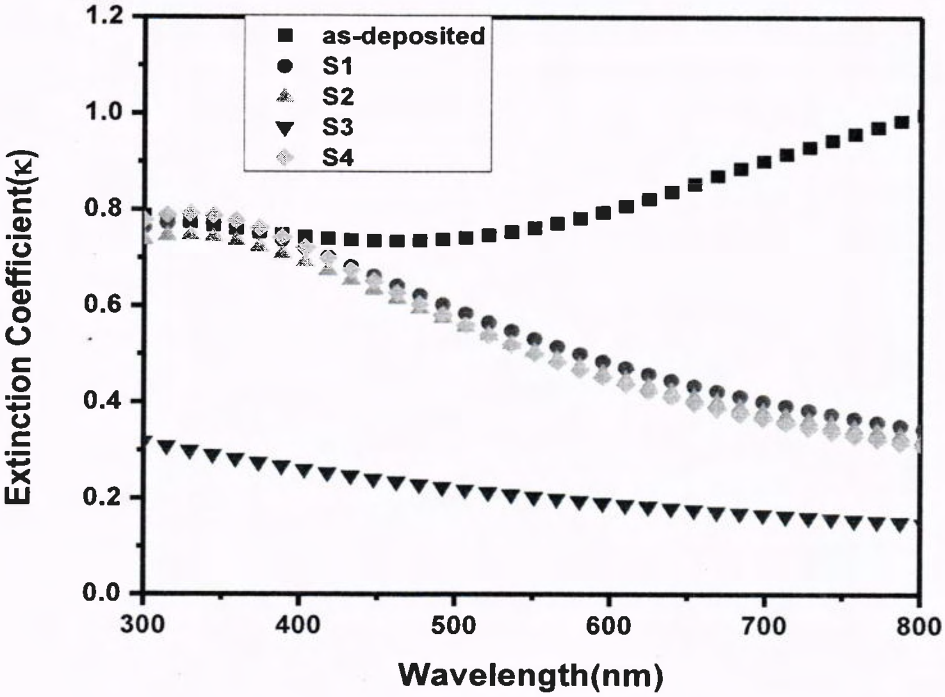


Figure 5. 18 Comparison of extinction coefficient of CdTe as deposited and coated samples

5.4.4 Absorption Measurements

The measurements were carried out on CdTe thin films with varying $SrCl_2$ concentrations. The absorption coefficient of CdTe thin film was measured by the equation (5.6).The graph shows a remarkable increase in the absorption of CdTe thin film after coating $SrCl_2$. Strong absorption was shown in shorter wavelength region. Increase in absorption means that $SrCl_2$ enabled CdTe thin film to absorb much more energy which is good for optical devices. Moreover it is an efficient solar material [112]. A higher absorption coefficient is beneficial for both economically and technically. Large values allows us to use a relatively thinner absorber layer so that lesser quantity of material was required [105].

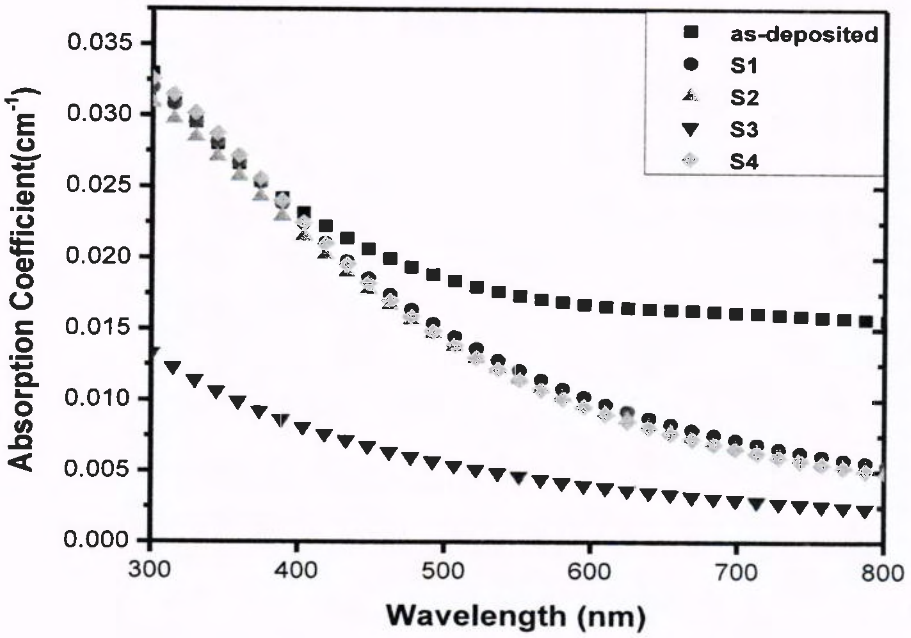


Figure 5. 19 Comparison of absorption coefficient of CdTe as deposited and coated samples

5.4.5 Refractive Index

The refractive index (n) and extinction coefficient (K) are used to describe the optical properties which defines the interaction of light with thin film. Optical absorption depends upon optical constants (n) and (k) [114]. Refractive index was measured by the following equation

$$n = n + iK \tag{5.7}$$

Figure 5.20 shown the variation of refractive index as a function of wavelength. It is observed that, refractive index of as-deposited film is 2.2 which decreased by the coating of $SrCl_2$. S3 coated sample shows different behaviour from other samples that refractive index is lower than all samples. The relation between refractive index (n) and optical bandgap energy (E_g) was shown by the equation [115]

$$n = KE_g^C \tag{5.8}$$

Where

K= 3.3668 and C= -0.32234 are constants

According to this relation refractive index (n) and optical bandgap (E_g) was directly related to each other. So, decrease in refractive index indicated the decrease in bandgap energy showing improvement in transmission which is beneficial for improving efficiency of CdTe as absorber layer in solar cell.

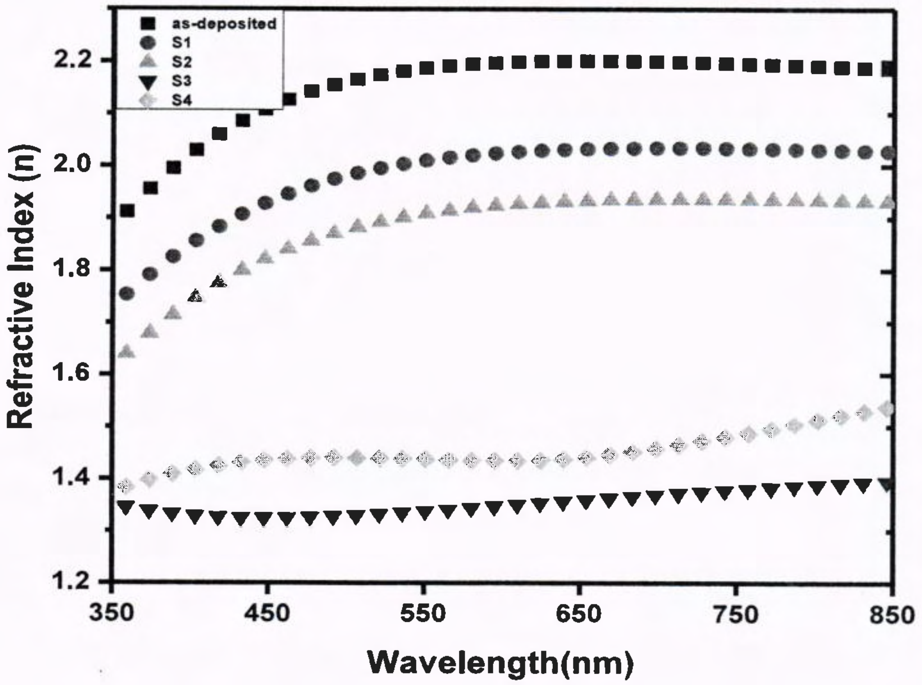


Figure 5. 20 Comparison of refractive index of CdTe as deposited and coated samples

5.4.6 Band gap energy measurements

Band gap was also measured by spectroscopic ellipsometry. The formula used for the band gap measurements is shown below [105].

$$\alpha h\nu = A(h\nu - Eg)^{N/2} \tag{5.9}$$

Here constant= A, photon energy = hv, optical band energy gap= E_g and N depends on the nature of the transition (N = 1 for direct band gap and N =4 for indirect band gap transition).

While [105]

$h\nu$ (eV) = 1240/nm

Bandgap was calculated by extrapolating $(\alpha h\nu)^2$ vs incident photon energy ($h\nu$) as shown in the Figure 5.21, 5.22, 5.23, 5.24, 5.25.

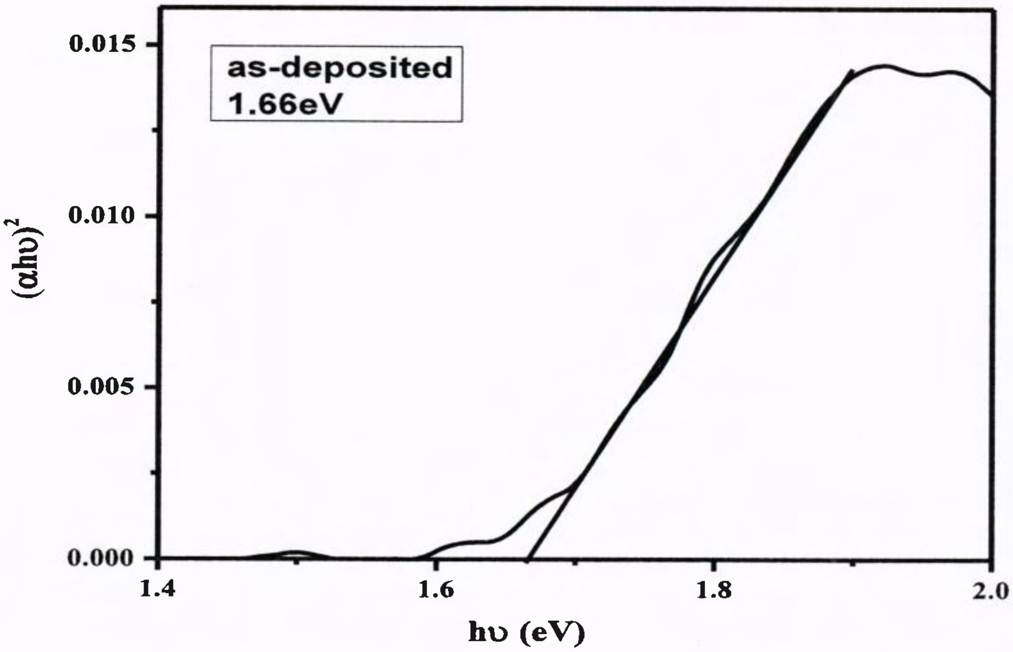


Figure 5. 21 Plotting band gap of CdTe thin film as deposited

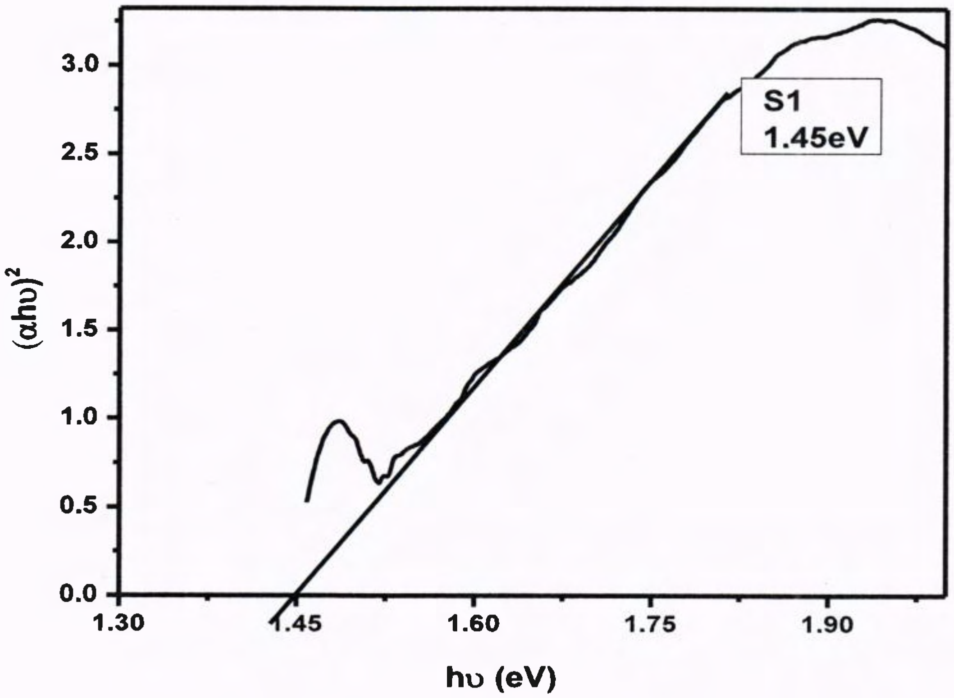


Figure 5. 22 Plotting bandgap of CdTe, S1 sample

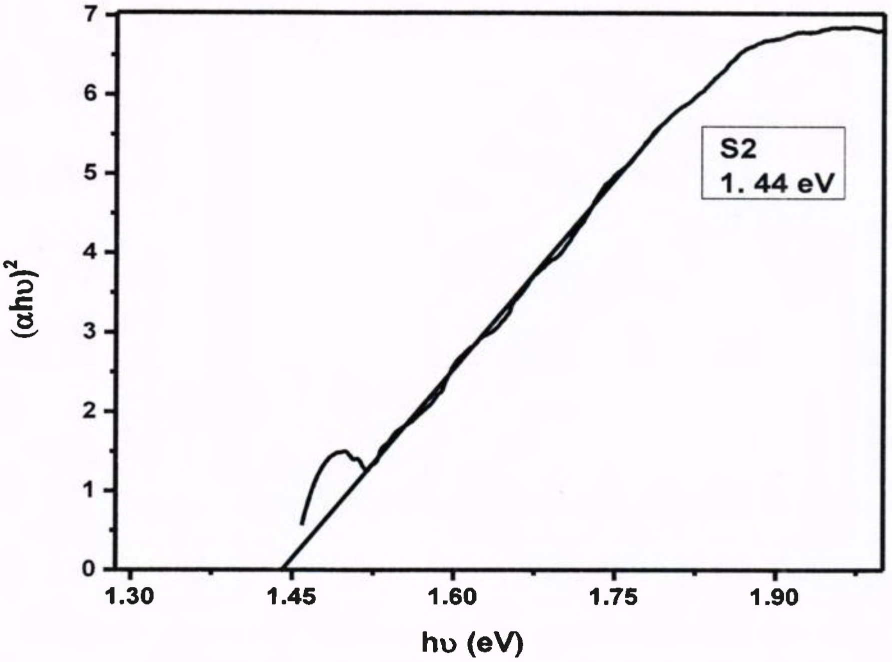


Figure 5. 23 Plotting bandgap of CdTe, S2 sample

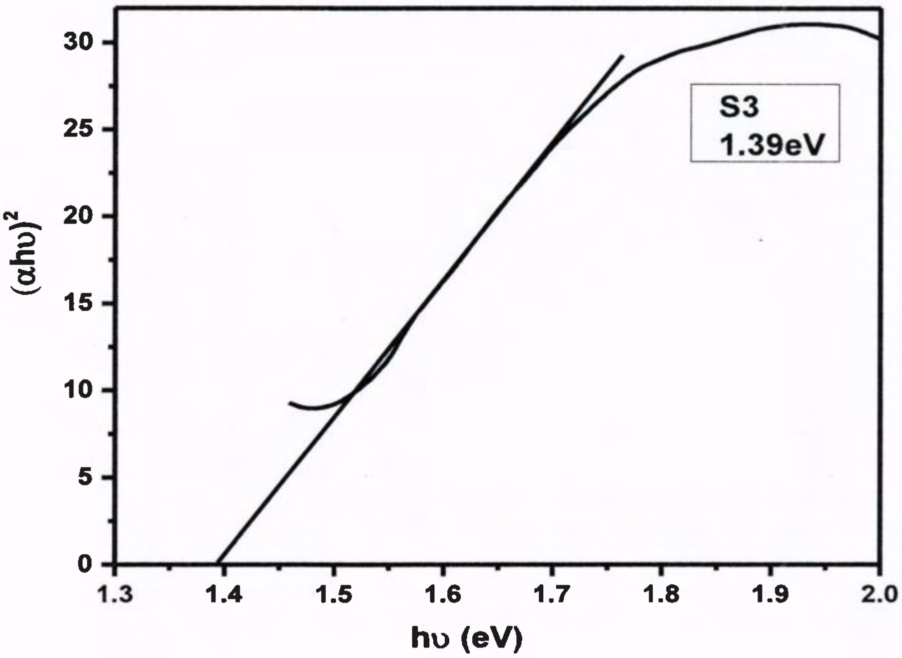


Figure 5. 24 Plotting bandgap of CdTe, S3 sample

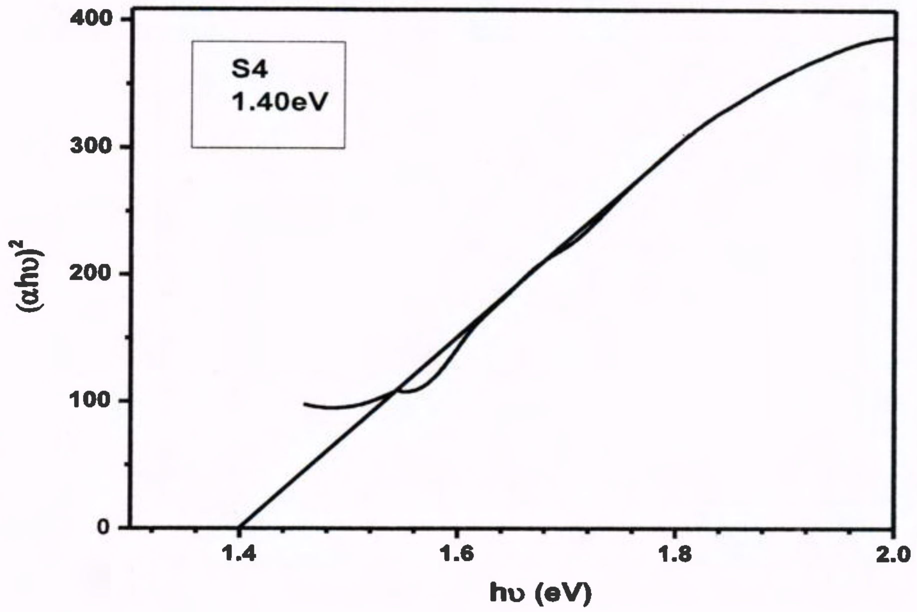
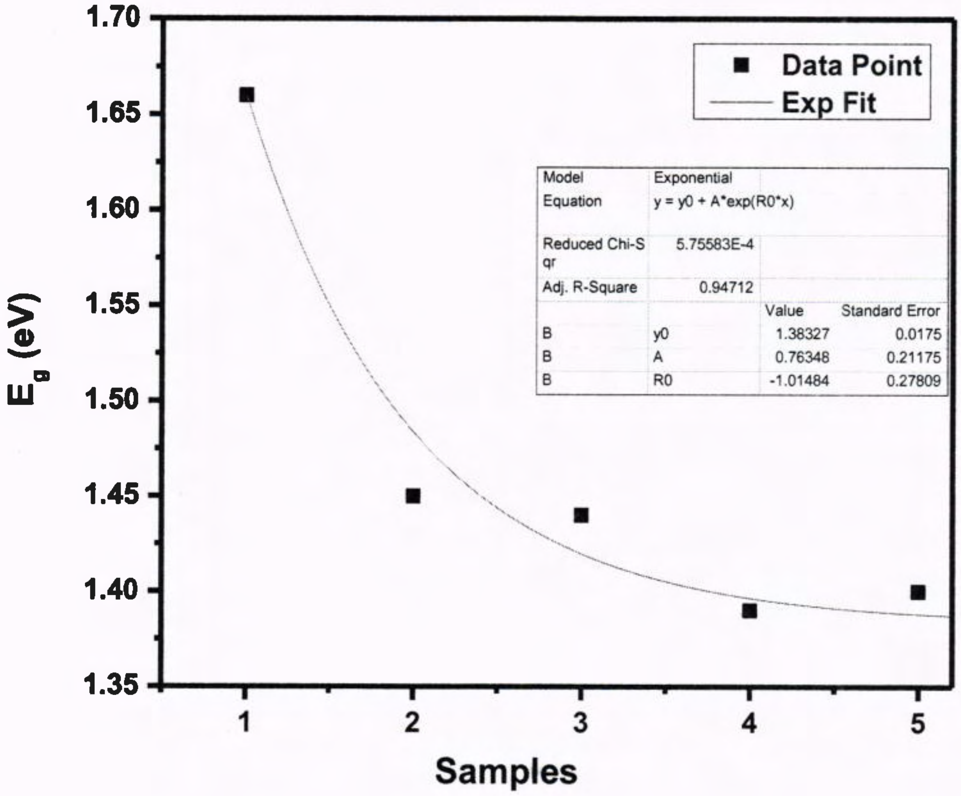


Figure 5. 25 Plotting bandgap of CdTe, S4 sample

The optical band gap obtained from the samples with exponential fit method and errors are plotted in Figure 5.26. The bandgap for as-deposited sample measured as 1.66eV, which was reduced to 1.4eV for coated samples. The change in bandgap was expected and the fall in the bandgap is function of the dopant's level. Reduction in bandgap indicates enhancement of transmission which is useful for enhancing CdTe layer efficiency in solar cell [106].



Model	Exponential		
Equation	y = y0 + A*exp(R0*x)		
Reduced Chi-Sqr	5.75583E-4		
Adj. R-Square	0.94712		
		Value	Standard Error
B	y0	1.38327	0.0175
B	A	0.76348	0.21175
B	R0	-1.01484	0.27809

Figure 5. 26 Plot of bandgaps of CdTe as deposited and $SrCl_2$ coated samples

5.5 Conclusion

We had demonstrated the effectiveness of non-toxic and inexpensive strontium chloride $SrCl_2$ as substitute of $CdCl_2$ activation treatment for CdTe thin film solar cells. CdTe/$SrCl_2$ bi-layer thin film was prepared using CSS and Spin Coating synthesis techniques. In comparative analysis we observed that a remarkable change was observed in structural, electrical and optical properties by coating $SrCl_2$. In XRD results, increasing grain size was observed with decrease in dislocation density and lattice strain. SEM images shows change in surface roughness, grain size and boundaries of CdTe. Increase in grain size was confirmed by SEM results. In I-V results increasing current with different $SrCl_2$ concentrations was measured. Current increases up to about 240nA, while as deposited CdTe layer showed only 7pA current. The optical properties were also enhanced i.e. absorption and refractive index was increased significantly and decrease in extinction coefficient was measured. Band gap was decreased significantly from 1.66eV to 1.40eV after coating which was much better than $CdCl_2$ treatment. According to the results and due to inexpensive and non-toxic character are proposed that $SrCl_2$ can be used as substitute for $CdCl_2$.

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