CHAPTER 5

RESULTS AND DISCUSSION FOR CADMIUM TELLURIDE-SELENIDE ($CdTe_xSe_{1-x}$)

5. RESULTS AND DISCUSSION FOR CADMIUM TELLURIDE-SELENIDE ($CdTe_xSe_{1-x}$)

The purpose of fabricating the ternary compound, ($CdTe_xSe_{1-x}$), is to attempt to improve the overall photovoltaic cell properties. The initial hypothesis was that a combination of the two binary materials, CdTe and CdSe, with energy gaps of 1.45eV and 1.74eV respectively, would result in a new material that would have an energy gap somewhere between these two values and better match the peak energy of the solar spectrum which is between 1.5-1.55eV (as seen in figure 1.19 in chapter 1).

In this chapter, a slightly different approach is taken in material preparation as many of the basic parameters and precautions have been clearly determined in chapter 3 and 4. The investigations that have been done were focused on the following points :

- The possibility of forming ternary compounds from the two binary compounds, CdSe and CdTe, by the electrodeposition method as well as by sputtering
- To investigate if the ternary compound formed here is of a single polycrystalline phase or a mixed phase of CdSe and CdTe.
- To study the effect on the overall energy gap (E_g) and refractive index (n) when the two basic binary compounds, having their respective E_g and n, are combined to form a new material
- The end effect on the photovoltaic properties were predicted to be improved by the formation of the ternary compound, $CdTe_xSe_{1-x}$. Therefore a full comparative study had to be done to compare the relevant values.

5.1 Analysis Procedure

The analysis procedure in this chapter differs from what is done at the experimental stage in chapter 3 and 4, as the effect of many variations had been observed and concluded. The experience enables the focus to be placed on composition integrity and not the fundamental parameters. The characterisation procedure was however applied once again in a similar manner.

5.1.1 Sequence of Events

1. The observation of the effect of variations on the deposited film was studied theoretically in past literature [64, 65, 87] and practically in the experiment in the last two sections on CdSe and CdTe deposition.

2. Once the necessary parameter such as deposition voltage, deposition time, bath temperature, materials for the working electrode and counter electrode are ascertained (as in chapter 3 and 4), it was concluded that the formation of $CdTe_xSe_{1-x}$ would actually require a variation in the concentration of component electrolytes and not voltage variation for stoichiometric purposes. Thus, the concentration variation was calculated and tested experimentally on the formation of the ternary compound with x taking the values of 0.25, 0.5 and 0.75. In a similar manner, it was also attempted to form CdTeSe in a 1:1:1 ratio by further adjusting the concentrations accordingly.

3. The films obtained were subjected to material characterisation procedures using XRD, EDX, SEM and UV/VIS spectrometry.

4. Electrical characterisation was done to observe the effect of stoichiometric variations on the photovoltaic cell performance.

5.2 Electrodeposition of Cadmium Telluride-Selenide ($CdTe_xSe_{1-x}$)

For effective electrodeposition of the ternary compound, the components of the electrodeposition process which were studied more closely were the electrodes, the aqueous electrolytic bath and the full electrochemical processes that take place.

5.2.1 The Electrolyte

The electrolyte has the function of providing cadmium, tellurium and selenium free ions to enable a deposition to take place when a voltage is applied through it via the electrodes. The behaviour of the electrolyte under various potentiostatic conditions were also studied and were based to a large extent on the experience gained in chapter 3 and chapter 4.

As it is extremely important to first study the dynamic reaction mechanisms occurring in the electrolyte, it is deemed necessary to first study the voltammograms of the individual reaction mechanisms of CdSe and CdTe. With these fundamentals, it is possible to then form assumptions on the global reaction of the combined $CdSO_4$, TeO_2 and SeO_2 component aqueous solutions in the electrolyte. The voltammograms presented in this thesis are made with reference to silicon as the working electrode.

We can conclude from the voltammogram and practical experience in chapter 3 and 4 that for $CdSO_4$ (or $CdCl_2$), which is at relatively high concentration at about 0.3M, the deposition of cadmium would normally begin at a voltage of -750mV. For TeO_2 and SeO_2, where the concentrations are relatively very low (1mM and 0.9mM respectively), the deposition behaviour is such that two main waves occur in the I-V curve, proposing two separate reactions. The first reaction, at about -400mV, corresponds to the reduction of $HTeO_2^+$ and $HSeO_2^+$, to form either a tellurium or selenium deposit on the cathode. The reaction associated with the second wave at about -700mV, can be attributed to the tellurium reduction into $H_2Te(aq)$ or $H_2Se(aq)$, which is not desired. The experiences in chapter 3 and 4 point to a strong agreement with this fact as the deposition of CdTe and CdSe showed good 1:1 stoichiometry for the codeposition voltage of -670mV and -650mV respectively.

This experience points out two major implementations in the deposition of the ternary compound of varying stoichiometry:

1. For the deposition of $CdTe_xSe_{1-x}$, from an electrolytic bath containing 0.3M $CdSO_4$, 1mM TeO_2 and 0.9mM SeO_2, it is best to apply a voltage of about -670mV to -650mV, to obtain good stoichiometry. The attempt to apply voltages beyond -700mV would result in cadmium rich films with hardly any tellurium or selenium depositions, due to the second wave reaction. Lower voltages would result in the inability of cadmium to deposit and hence result in tellurium and selenium rich films, which are also not desired.

2. For the purpose of varying the stoichiometry of $CdTe_xSe_{1-x}$, by using x values of 0.25, 0.5 and 0.75, it is not feasible to apply voltage variations due to the voltammogramic behaviour. Instead, the modification of the stoichiometry should be done at the concentration level of the component salts.

The global reaction mechanism for the formation of the ternary compound is given below :

$$Cd^{2+} + HTeO_2^+ + HSeO_2^+ + 6H^+ + 10e^- \rightarrow CdTeSe + 4H_2O$$

The silicon electrodes should not be placed for long periods of time in the electrolyte as it could cause the formation of selenium and tellurium on the electrodes, even under open circuit conditions. This can be explained by a corrosion mechanism, which is shown in a coupled redox reaction below :

Oxidation mechanism : $Si + 2H_2O \rightarrow SiO_2 + 4H^+ + 4e^-$

Reduction mechanism : $HTeO_2^+ + 4e^- \rightarrow Te + 2H_2O$

$HSeO_2^+ + 4e^- \rightarrow Se + 2H_2O$

To avoid this corrosion mechanism from taking place, the potential to the electrodes was applied before immersion into the electrolyte and only switched off when the electrodes were removed from the electrolytic bath.

The cathodic polarisation characteristics described in chapter 2 and practically experimented in chapter 3 and 4 show full agreement with the voltammogramic investigations. It is therefore assumed that the associated data can be applied in understanding and determining the codeposition voltage of cadmium, tellurium and selenium ions.

The starting chemicals and their respective concentrations for the deposition of the ternary compound is shown below.

1. $CdSO_4$	0.3M
or $CdCl_2$	0.3M
2. TeO_2	1 mM
3. SeO_2	0.9mM
4. EDTA	15mM

Due to the low solubility of TeO_2, it is first dissolved in H_2SO_4 when $CdSO_4$ was used, or HCl when $CdCl_2$ was used. The addition of this acid into the electrolyte also assuresd an acidic media for the electrolyte, which is suitable for the electrodeposition of cadmium based thin films. EDTA is added as a complexing agent for the electrolyte.

5.2.2 The Electrodes

The electrodeposition of cadmium based films is basically a cathodic deposition. In this research, various grades of silicon were experimented as the working electrode for the sole purpose of attaining the best solar energy conversion characteristics. Parallel depositions was also made on conducting ITO glass as a transparent substrate is required for optical characterisation purposes.

Since the paces of identifying the most appropriate type of silicon substrate has already been done in chapter 3 and 4, it will not be repeated here. Type V wafers, with a resistivity of 9.6Ωcm^{-1} (p-type), was used as the working electrode for all electrodepositions here, as well as the substrate for the sputtered samples. This wafer grade was found to yield the best photovoltaic performance.

Copper plates were used as counter electrode (anode) as it had been proven experimentally in chapter 3 that it had a favourable effect on the deposition current as compared with platinum and silicon. Since copper had the tendency to rapidly oxidise and diffuse into the electrolyte and the deposited film, certain precautions had to be taken. Two steps were taken to counter this problem, where firstly, the deposition time is not allowed to exceed ten minutes and secondly, the electrodes were replaced with freshly cleaned ones at 3-5 minutes intervals. These steps largely reduce or eliminate the diffusion of undesired copper in the deposited films, which could become potential current collectors and reduce electron mobility, as well as cause leakages at the p-n junction interface

5.3 The Electrodeposition Process

The variations in the stoichiometry of the ternary compound, $CdTe_xSe_{1-x}$, was done by concentration variations as the outcome of voltammogramic and cathodic polarisation studies. Since many of the deposition parameter variations had been clearly experimented and observed in earlier sections, the following parameters were fixed.

- A voltage of 650-670mV is applied. From experimental and voltammogram studies, it was found to be the most suitable for cadmium based film depositions.
- Type V silicon was used in all cases as it yielded the best photovoltaic properties in the solar cell analysis.
- Copper is used as the counter electrode and changed at 3-5 minutes intervals during the deposition.
- The total deposition time is typically 10-15 minutes for a reasonably thin film for solar cell applications.
- The electrolytic bath temperature is maintained at 57°C for better film adhesion and continuously stirred at 50rpm for uniform free ion density and steady temperature distribution.

Upon fixing these parameters, calculations were made on the required salt concentrations for various stoichiometry. It was found that the most convenient manner in which this can be done is to first make stock solutions of 0.3M $CdSO_4$ (or $CdCl_2$), 0.9mM SeO_2 and 1mM TeO_2 and vary the respective volumes in the electrolytic bath to achieve the desired stoichiometry. The outcome of these calculations is tabulated below.

Table 5.1 Volume of Various Electrolyte Components to Achieve Different x Values for $CdTe_xSe_{1-x}$

$CdTe_xSe_{1-x}$	Volume		
	0.3M of $CdSO_4$ (or $CdCl_2$) (ml)	1mM of TeO_2 (ml)	0.9mM of SeO_2 (ml)
x = 0	25	-	25
x = 0.25	25	6.25	18.75
x = 0.5	25	12.5	12.5
x = 0.75	25	18.75	6.25
x = 1	25	25	-
CdTeSe, 1:1:1	15	15	15

It can be observed that when x = 0, CdSe is formed and when x = 1, CdTe is deposited. These two steps of working on x = 0 and x = 1 were not done, as it is a repeat of the findings in chapters 3 and 4. Films of $CdTe_xSe_{1-x}$ was fabricated for values of x = 0.25, 0.5 and 0.75, as well as a stoichiometric compound of CdTeSe, where the ratios of Cd:Te:Se ions is 1:1:1.

These fabricated films were then thoroughly rinsed in distilled water, dried and subjected to various material and electrical characterisation processes.

5.4 Electron Beam Sputtering of $CdTe_{0.5}Se_{0.5}$

The purpose of sputtering cadmium based films, is to make a comparative analysis on the physical, optical and electrical properties as opposed to electrodeposited films. The thin films of $CdTe_{0.5}Se_{0.5}$ is obtained by sputtering techniques identical to that in section 3.4. The starting chemicals were analar grade granules of CdTe (99.99% purity) and CdSe (99.99% purity).

For obtaining films of a stoichiometry of $CdTe_{0.5}Se_{0.5}$, equal amounts of CdTe and CdSe granules were weighed and placed in the carbon hearth. For this purpose, only equal sized granules were selected to maintain a consistency in terms of the surface area. These granules were then mixed for a uniform distribution. The films were sputtered in type V silicon for electrical and physical characterisation purposes and on glass for optical characterisation.

5.5 Material Characterisation

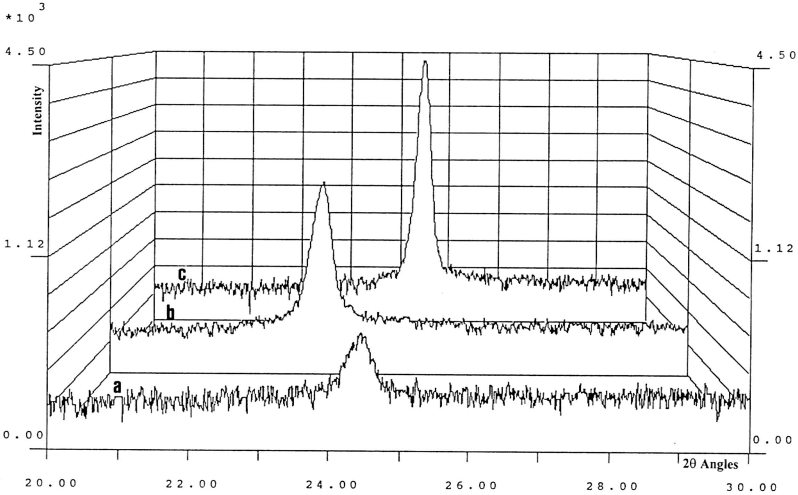
5.5.1 X-Ray Diffractometry

The study of the X-ray diffraction pattern is of great significance in this study as the ternary compound, $CdTe_xSe_{1-x}$, has not been reported before. The following samples were picked out for diffraction studies :- $CdTe_xSe_{1-x}$ thin films sputtered on silicon and glass, as well as films electrodeposited on silicon and ITO.

The theoretical and experimental values for major peaks of CdTe and CdSe are at 23.68°(111) and 25.4°(111) and are of the cubic phase (zinc blend structure). Figure 5.1 shows the diffractogram of sputtered $CdTe_{0.5}Se_{0.5}$ (5.1a) on silicon, as compared to sputtered CdTe (5.1b) and sputtered CdSe (5.1c). Figures 5.1b and 5.1c are that obtained from chapter 3 and 4. A distinct peak is observed for sputtered $CdTe_{0.5}Se_{0.5}$ which does not coincide with that of CdSe and CdTe, but lies somewhere in between at a 2θ angle of 24.5°. We can hereby conclude that the new $CdTe_{0.5}Se_{0.5}$ results in phase alteration of CdSe and CdTe, and creates a new highly polycrystalline phase of its own with a peak at 24.5°. Therefore the lattice spacing (d) of the new compound, $CdTe_xSe_{1-x}$, is approximated to be 3.63Å.

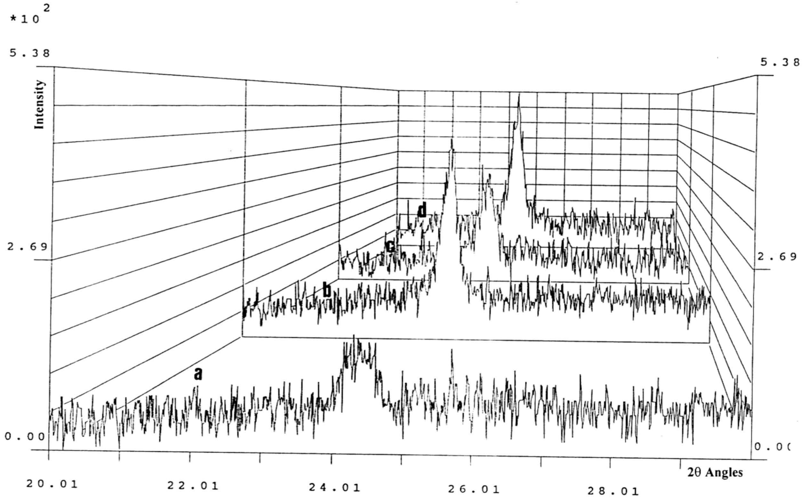
Figures 5.2(a-d) show the diffractogram of $CdTe_{0.5}Se_{0.5}$ sputtered on silicon (5.2a) and on glass (5.2c). Figures 5.2b and 5.2d are the diffractograms of the respective samples after annealing. All angles coincided with the new value of 24.5° for $CdTe_{0.5}Se_{0.5}$. The effect of annealing at 473K for two hours in vacuum results in increased grain size and transitions from metastable to stable phases , thus resulting in higher intensities.

Figure 5.1 : XRD of $CdTe_XSe_{1-X}$ Compared to CdTe and CdSe Sputtered on Silicon



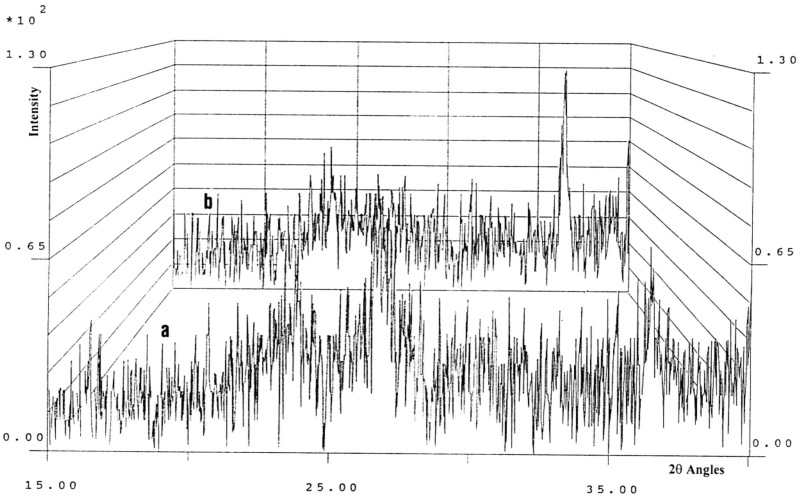
a: $CdTe_XSe_{1-X}$ Thin Film on Si, b: CdTe Thin Film on Si, c: CdSe Thin Film on Si

Figure 5.2 : XRD of CdTe$_{0.5}$ Se$_{0.5}$ Sputtered on Silicon and Glass



a: Thin Film, b: Thin Film Annealed, c: Thick Film, d: Thick Film Annealed

Figure 5.3 : XRD of $CdTe_{0.5}Se_{0.5}$ Electrodeposited on Silicon and ITO



a: Thin Film deposited on Si. b: Thin Film deposited on ITO

Figures 5.3(a and b) show the diffraction patterns of $CdTe_{0.5}Se_{0.5}$ electrodeposited on silicon and ITO. Once again, distinct peaks at 24.5° were observed, confirming the formation of the desired compound. The peaks were of low intensities and thus, having a poorer peak to background ratio. Some additional peaks from ITO (38°) and CdSe (25.4°) are also observed, but are less dominant.

As a conclusion, it can be said that the prediction that a new phase of material will be formed in the ternary compound, has been proven by the presence of a single new peak. Even though concentrations of $CdTe_xSe_{1-x}$ have been varied for $x = 0.25$, 0.5 and 0.75, the major peak remained at approximately 24.5° and therefore not presented here. EDX analysis had however, proven that there was a change in concentration ratios with the value of x and will be discussed in the following section.

5.5.2 Energy Dispersive Analysis of X-Rays (EDX)

The EDX technique was used here to study the quantitative changes of elemental concentrations in the deposited films. The effects of deposition voltage and time were not studied here, as it had been well ascertained in chapters 3 and 4 and is maintained here. Figures 5.4(a-e) show the EDX spectra for $CdTe_xSe_{1-x}$ where x was varied by changing the respective chemical concentrations. In figure 5.4a, the chemical concentrations were altered for x to take a value of 0.25, resulting in $CdTe_{0.25}Se_{0.75}$. This spectra shows that cadmium had a 50% overall concentration, but the film in general had become selenium rich. In figure 5.4b, x was adjusted to 0.5, therefore forming $CdTe_{0.5}Se_{0.5}$. Once again, cadmium had an approximately 50% composition and equal amounts of selenium and tellurium were found. At $x = 0.75$, the film became $CdTe_{0.5}Se_{0.5}$ and can be observed to be tellurium rich (figure 5.4c).

The approach was taken a step further to form CdTeSe in a 1:1:1 ratio (figure 5.4d) by, again, simply adjusting the concentration. The EDX data shows that a very close match was obtained to the theoretical values. The sample prepared by the sputtering method also displayed close relevance to the theoretical value (figure 5.4e). The x value was approximated at 0.5, as equal amounts of CdTe and CdSe granules were placed in the carbon hearth before sputtering.

The presence of copper is observed in figures 5.4a and 5.4b. The presence of this material is undesired and is probably due to delays in electrode replacement or longer deposition times. Copper atoms diffused in the film could act as electron traps and reduce the end solar cell performance.

The table shows the concentration of cadmium, selenium and tellurium in weight percentages for $CdTe_xSe_{1-x}$, for various values of x. The sample were coated at 0.67V for 10-15 minutes at a bath temperature of 57°C. All substrates used were type V silicon with copper counter electrodes.

Table 5.2 Elemental Composition of $CdTe_xSe_{1-x}$ for Various Values of x (Theoretical Values Compared to Experimentally Obtained)

$CdTe_xSe_{1-x}$	**%Cd**		**%Te**		**%Se**	
	EDX Data	**Theoretical**	**EDX Data**	**Theoretical**	**EDX Data**	**Theoretical**
x = 0.25	50.02	50	13.57	12.5	36.41	37.5
x = 0.5	58.07	50	16.65	25	25.59	25
x = 0.75	53.06	50	37.25	37.5	9.69	12.5
CdTeSe (1:1:1)	33.06	33.3	34.2	33.3	32.74	33.3
Sputtered (x = 0.5)	48.41	50	27.65	25	23.96	25

The results obtained from the EDX spectrum show a very good correlation with theoretically expected values for both the sputtered and electrodeposited thin films. This conclusively proves that the electrodeposition method is an effective way of producing films of accurate elemental composition.

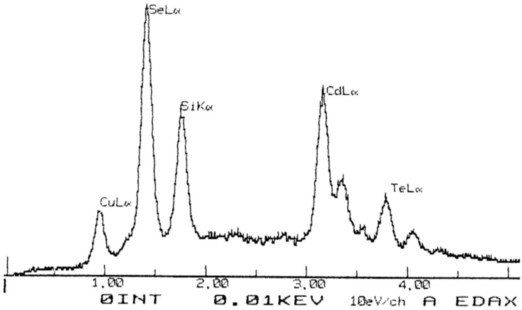


Figure 5.4a : EDX Spectra for $CdTe_XSe_{1-X}$ Electrodeposited on Si (X=0.25)

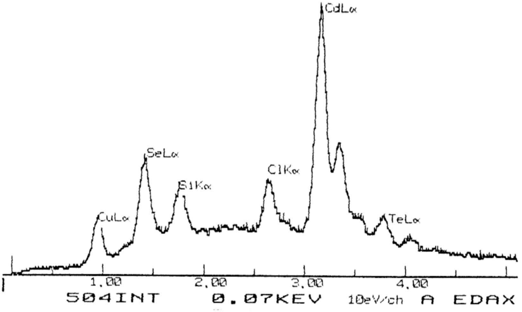


Figure 5.4b : EDX Spectra for $CdTe_XSe_{1-X}$ Electrodeposited on Si (X=0.5)

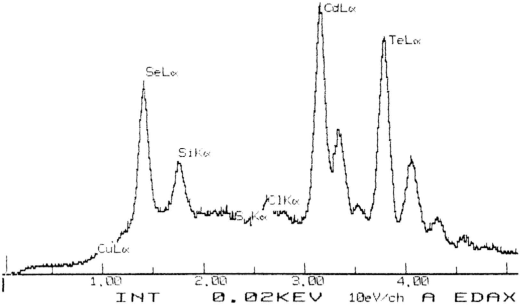


Figure 5.4c : EDX Spectra for $CdTe_XSe_{1-X}$ Electrodeposited on Si (X=0.75)

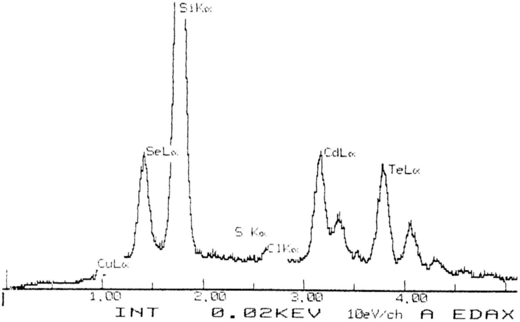


Figure 5.4d : EDX Spectra for CdTeSe Electrodeposited on Si (at 1:1:1 ratio)

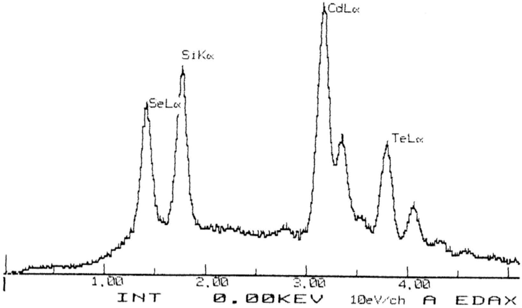


Figure 5.4e : EDX Spectra for $CdTe_XSe_{1-X}$ Sputtered on Si (X=0.5)

5.5.3 Scanning Electron Microscopy (SEM)

Several samples were chosen for surface morphology and grain size observations. $CdTe_{0.5}Se_{0.5}$ films electrodeposited on silicon and ITO, as well as that sputtered on silicon, were observed more closely.

Figure 5.5a and 5.5b are micrographs of $CdTe_{0.5}Se_{0.5}$ sputtered on type V silicon at magnifications of 12000X and 15000X. Even though the grain size is not evenly distributed, the sample is observed to be minimally porous with very few distinguishable surface particles (light contrast) with the bulk particles (dark contrast). The grain sizes take on a large distribution, ranging from <0.1μm up to 0.3μm. This large variation of particle sizes could originate from the fact that three different elements were simultaneously sputtered causing various crystallite formations.

Figures 5.6a and 5.6b show the micrographs of $CdTe_{0.5}Se_{0.5}$ electrodeposited on type V silicon at 10000X and 15000X. A very uniform grain size distribution was observed but revealed rather high porosity. The average grain size is estimated to be approximately 0.1μm. Figure 5.7a and 5.7b are micrographs of $CdTe_{0.5}Se_{0.5}$ at 150000X and 30000X electrodeposited on ITO. The fact that the particle sizes are larger and the porosity much lower leads to the assumption that the ITO film has an effect on the subsequent formed film. The particle size is estimated to be about 0.2-0.4μm.

An interesting fact that can be concluded from the SEM micrographs is that even though an identical film was coated, the end morphology and particle size distributions are highly dependant on the deposition technique (eg. electrodeposition, sputtering) and also the substrate type and surface structure.

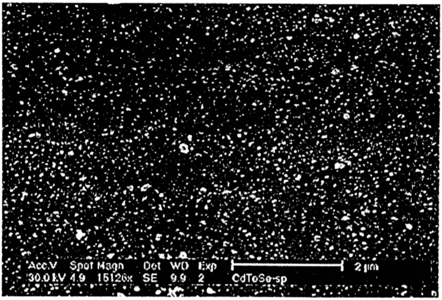


Figure 5.5a : Micrograph of CdTe$_X$Se$_{1-X}$ Thin Film Sputtered on Silicon (11693X)

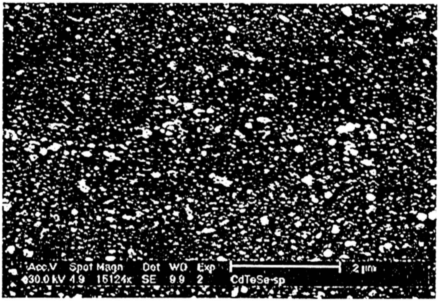


Figure 5.5b : Micrograph of CdTe$_X$Se$_{1-X}$ Thin Film Sputtered on Silicon (15000X)

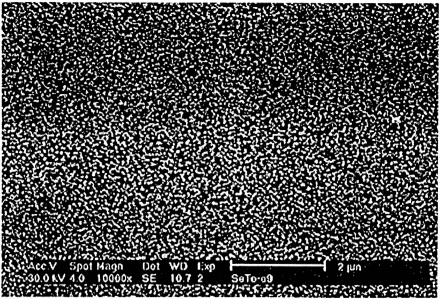


Figure 5.6a : Micrograph of $CdTe_XSe_{1-X}$ Thin Film Electrodeposited on Silicon (10000X)

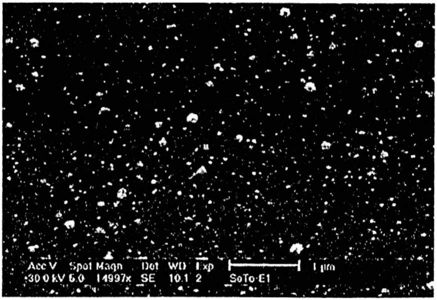


Figure 5.6b : Micrograph of $CdTe_XSe_{1-X}$ Thin Film Electrodeposited on Silicon (14997X)

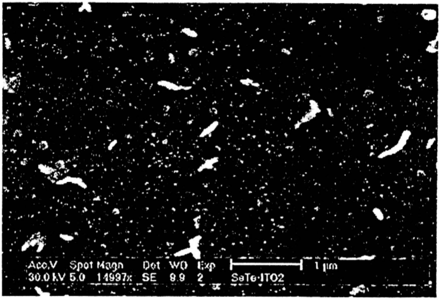


Figure 5.7a : Micrograph of CdTe$_X$Se$_{1-X}$ Thin Film Electrodeposited on ITO (15000X)

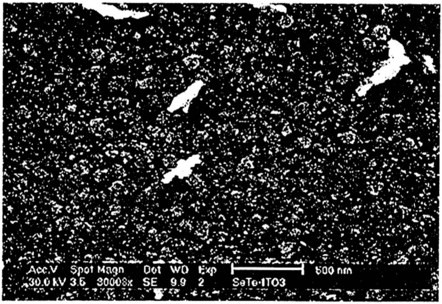


Figure 5.7b : Micrograph of CdTe$_X$Se$_{1-X}$ Thin Film Electrodeposited on ITO (30000X)

5.5.4 UV-Visible Spectroscopy

The optical characterisation of $CdTe_xSe_{1-x}$ was obtained by studying the transmission and absorption spectra. The transparent substrates used were films electrodeposited on ITO and sputtered on glass.

The refractive index (n), absorption coefficient (α) and film thickness (t) was obtained by calculations using the envelope method. Figure 5.8 shows the transmission spectra of four films, two of electrodeposited on ITO (figures 5.8c and 5.8d), and two more sputtered on glass (5.8a and 5.8b). Since the objective of formulating the films were to achieve high quality solar cells, the thin nature is reflected by the lack of transmission fringes. Therefore the properties of n, α and t were calculated solely for the thicker films. An example of the transmission fringe fitted for n, α and t calculations is shown in figure 5.9.

The lack of multiple fringes in the transmission spectra makes it very difficult and presumptuous to calculate the energy gap, E_g, from the $(\alpha hf)^2$ versus energy plot due to the lack of plotting points. Therefore the E_g is found by extrapolating the absorption edge of the absorption spectra to the wavelength axis and converting the values into energy (eV).

Figure 5.10(a-d) shows the absorption spectra of the same four samples as above. The noticeable trend is that the absorption edges, even though of different gradients, have a tendency to intersect with the wavelength axis in the region of 800-870nm. Two individual curves were plotted (figures 5.11a and 5.11b) to investigate the intersection with the x-axis to obtain the energy gap of the material.

All the results obtained are tabulated in the table below. There are no references made to known materials as the ternary compound of $CdTe_xSe_{1-x}$, is being researched for the first time in this piece of work. The calculated energy gap from the transmission fringes and from the absorption edge show values ranging from 1.52-1.62eV, which is in between the values of CdTe (1.45eV and 1.74eV). The same observation can be made for the refractive index values.

Table 5.3 Optical Properties of $CdTe_xSe_{1-x}$

Sample	Calculated Refractive Index	Calculated Energy Gap (eV)	Calculated Thickness (nm)
$CdTe_{0.5}Se_{0.5}$ electrodeposited on ITO (thicker)	2.62	1.62	612
$CdTe_{0.75}Se_{0.25}$ electrodeposited on ITO (thicker)	2.59	1.52	±300
$CdTe_{0.5}Se_{0.5}$ sputtered on glass (thicker)	2.65	1.64	824
$CdTe_{0.5}Se_{0.5}$ sputtered on glass (thinner)	2.63	1.60	±400

In conclusion, we can say that the ternary compound, $CdTe_xSe_{1-x}$, has successfully altered the band gap of CdTe and CdSe to better match the peak of the solar radiation spectra. It is thus expected that the ternary films would have better solar efficiency.

Figure 5.8 : Transmission Spectra (T%) of CdTe$_x$Se$_{1-x}$ Sputtered on Glass and Electrodeposited on ITO

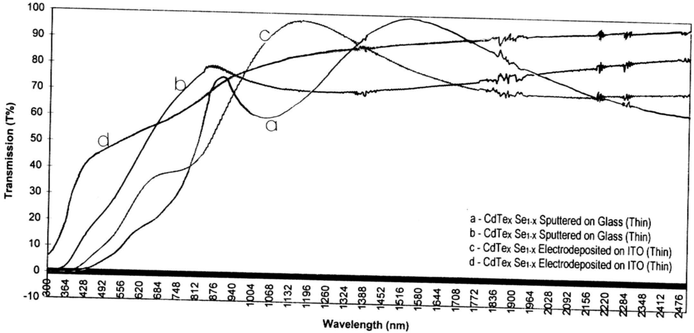


Figure 5.9 : Transmission Spectra of $CdTe_xSe_{1-x}$ Sputtered on Glass (Showing fitting for the envelope method)

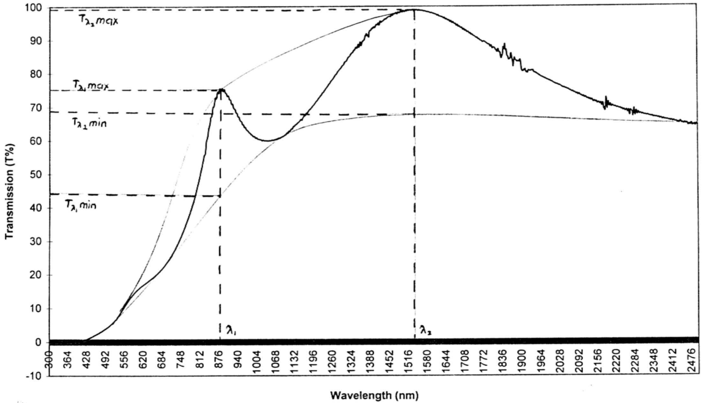


Figure 5.10 : Absorption Spectra of CdTe$_x$Se$_{1-x}$ Sputtered on Glass and Electrodeposited on ITO

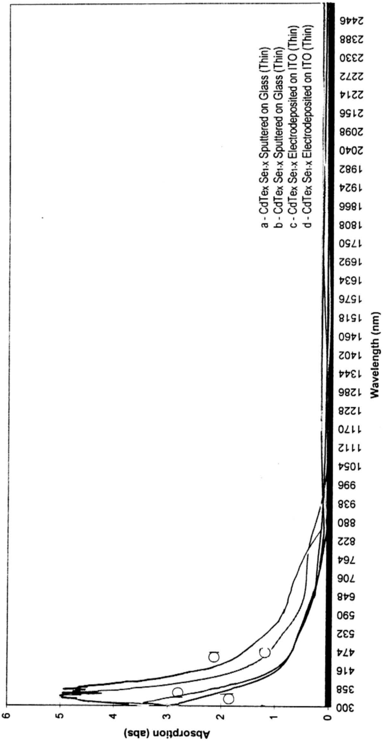


Figure 5.11a : Absorption Spectra of CdTe$_x$Se$_{1-x}$ Sputtered on Glass

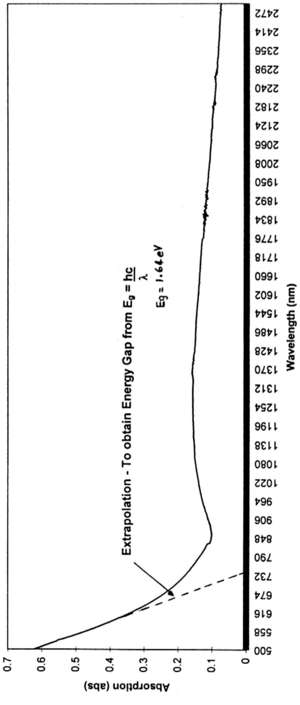
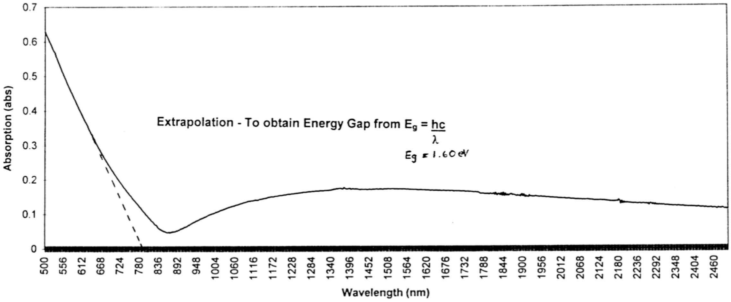


Figure 5.11b : Absorption Spectra of $CdTe_xSe_{1-x}$ Electrodeposited on ITO



5.6 Electrical Characterisation

5.6.1 Open Circuit Voltage (OCV) and Short Circuit Current (I_{SC})

The main interest behind researching the ternary material, $CdTe_xSe_{1-x}$, is to identify the possibility of fabricating a thin film for solar energy absorbing purposes, which could be superior to that of the two binary compounds, CdTe and CdSe, that it is made of. This would bring a very large emphasis and significance for this section because comparative studies are discussed here between the ternary and the basic binary compounds.

The necessity to compare the efficiency of the various wafer types does not arise here as the type V wafer has been identified as the most appropriate. For the purpose of further analysis, three films were selected: $CdTe_{0.25}Se_{0.75}$ and $CdTe_{0.5}Se_{0.5}$ electrodeposited on type V silicon and $CdTe_{0.5}Se_{0.5}$ sputtered on type V silicon. The OCV and I_{SC} of these films as compared to that of CdTe and CdSe was measured as described in chapter 2 and tabulated below. The figures for CdTe and CdSe are obtained from chapters 3 and 4.

Table 5.3 The OCV and I_{SC} of $CdTe_xSe_{1-x}$, As Compared To CdTe and CdSe

Sample	**Open Circuit Voltage, OCV (mV)**	**Short Circuit Current, I_{SC} (μA)**
Sputtered CdTe	295	2.45
Sputtered CdSe	275	2.2
Sputtered $CdTe_{0.5}Se_{0.5}$	340	2.6
Electrodeposited CdTe	250	2.21
Electrodeposited CdSe	260	2
Electrodeposited $CdTe_{0.5}Se_{0.5}$	310	2.35
Electrodeposited $CdTe_{0.75}Se_{0.25}$	320	2.43

The first indicator observed from the table is that the ternary compounds shows a moderate improvement in OCV and I_{SC}, as compared to the binary compounds. This observation is consistent for both electrodeposited and sputtered films.

5.6.2 Current Voltage (I-V) Characteristics

The I-V characteristic curve is obtained by measuring the total circuit current and the voltage across the solar cell, while varying the external load. The significance of this curve is that we are able to note the maximum power deliverable from the cell, as well as note the losses due to shunt and series resistance when compared to an ideal curve.

The I-V curve for the sputtered samples and electrodeposited samples for both the respective ternary and binary compounds were plotted separately in figures 5.12 and 5.13. In figure 5.12, we can comparatively see that the sputtered $CdTe_{0.5}Se_{0.5}$ ternary compound has an improved curve with a higher area below the curve especially when compared with the curve for CdTe and CdSe.

Figure 5.13 shows the I-V curve of electrodeposited $CdTe_{0.75}Se_{0.25}$ and $CdTe_{0.5}Se_{0.5}$. Once again it can be observed that the ternary compounds generally display superior power characteristics as compared with the binary CdTe and CdSe. The ternary compound of $CdTe_{0.75}Se_{0.25}$ shows a marginally better performance when compared to $CdTe_{0.5}Se_{0.5}$. When their energy gaps were observed from the optical characterisation studies, it was seen that the energy gap of $CdTe_{0.75}Se_{0.25}$ was 1.52 eV and closer matches the peak of the solar radiation as compared to $CdTe_{0.5}Se_{0.5}$ (1.62eV). This fact coupled with the thickness factor where the first film is thinner, has contributed to the slightly improved performance of $CdTe_{0.75}Se_{0.25}$ as compared to $CdTe_{0.5}Se_{0.5}$.

Figure 5.12 : I-V Characteristic Curve of $CdTe_xSe_{1-x}$ Sputtered on Silicon

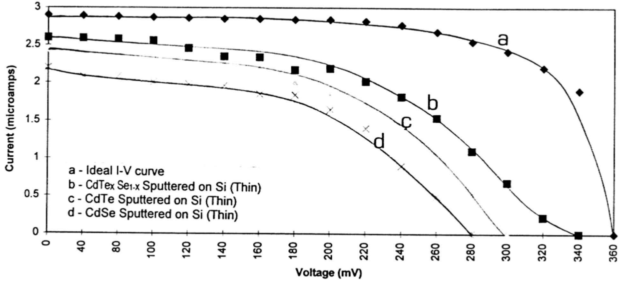
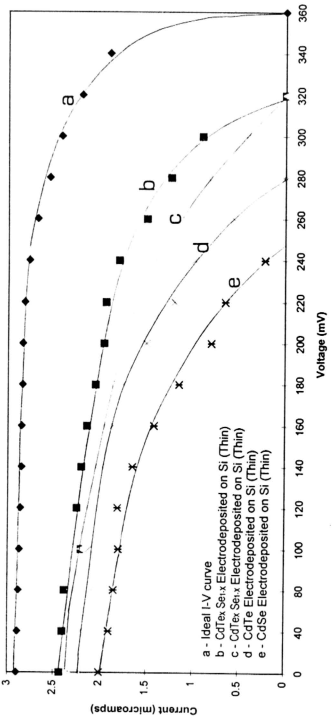


Figure 5.13 : I-V Characteristic Curve of CdTe Se Electrodeposited on Si



5.7 Electrodeposition of Large Area Solar Cells

In this section, it is demonstrated how the electrodeposition method can be scaled up quite easily for the purpose of the fabrication of large area solar cells. Figure 5.14 shows a photograph of the apparatus setup for the fabrication of a large area solar cell. The only notable difference from the basic setup used as shown in figure 2.1 in chapter 2 is that a larger container fabricated from perspex is used. The function of this setup is to fabricate an 8" solar cell (type V) obtained as a waste piece from a local semiconductor company. The identical voltages, deposition times, counter electrodes and chemical composition were used as in the deposition of $CdTe_{0.75}Se_{0.25}$.

Figure 5.15 is a photograph of the 8" silicon wafer upon ten minutes of electrodeposition (centre). A uniform formation of the film is observed with the film resembling exactly what was obtained for the smaller sized films in the experimental stages. The wafer on the left is coated for 5 minutes resulting in a thin coating. The wafer on the right was uncoated. This clearly shows how the electrodeposition method can be scaled up for large area deposition purposes.

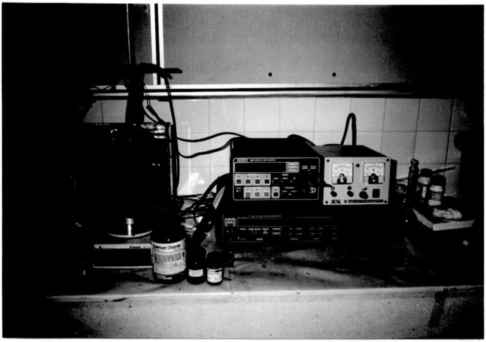


Figure 5.14 : Photograph of the Apparatus Setup for Preparation of Large Area Solar Cells

Figure 5.15 : Photograph of the Electrodeposited 8" Silicon Wafer

5.8 Conclusion For The Formation of Ternary Compounds

This study conclusively proves several key points:

- It is possible to actually form a ternary compound of a single phase by combining two binary compounds. In terms of the energy gap obtained, it has taken a value in between the individual energy gaps of the two binary compounds. It is thus possible to engineer the energy gaps by mere alterations of the chemical composition.

- these ternary compounds can be formed quite easily by the methods of sputtering and electrodeposition. The focus in this research is in the electrodeposition method as it is a relatively inexpensive low temperature process and was found to produce films of high quality in a short period of time. Expensive equipment and vacuum apparatus is also not required as in the sputtering and other high temperature methods.

- In terms of the quality of the film formed, the photovoltaic performance of electrodeposited films are comparable to films formed by the sputtering. Slight advantages of morphology and lower porosity gives a marginally improved performance of sputtered solar cells. However, if the electrodeposition method is refined further by periodic pulse deposition and lower deposition currents, it is possible to improve the quality of the solar cells even further.

- The electrodeposition process can easily be scaled up for the purpose of fabricating large area solar cells of high quality in an extremely cost effective manner. This gives a commercial perspective to this research as it has been shown how waste wafers can be utilised for large area deposition purposes.