Chapter – V

Experimental studies on Transparent conducting Cd$_2$SnO$_4$ thin films

5.1 Introduction

Transparent conducting oxides (TCOs) are an essential part of technologies that require large area electrical contact and optical access in the visible portion of the light spectrum. High transparency, combined with the useful electrical conductivity ($>10^3 \Omega^{-1} \text{cm}^{-1}$) is achieved by selecting a wide band gap oxide and its properties are altered by introduction of native or substitutional dopants. In the sense, cadmium tin oxide (Cd$_2$SnO$_4$) films play a major role because of its unique optical and electrical properties. Further, the device performance of Cd$_2$SnO$_4$ films depend on its structural, surface compositional, surface morphological properties with the electrical and optical properties. These material properties also require the inspection of preparation conditions as well. The present study deals with the structural, surface morphological, compositional, thermal, optical and electrical properties of Cd$_2$SnO$_4$ thin films as a function of preparation conditions to explore its device performance.

The Cd$_2$SnO$_4$ films were prepared on glass substrates by the RF magnetron sputtering technique. The film preparation parameters of RF magnetron sputtering such as target to substrate distance, argon flow were optimized to get uniform, pin hole free, well adherent and transparent films. The parameters such as substrate temperature and RF power are altered to get device quality films, as these parameters significantly affects the film properties of the Cd$_2$SnO$_4$ films. Hence, to study the effect of substrate temperature on the film properties, Cd$_2$SnO$_4$ films were deposited at room temperature (RT), 100 °C, 200 °C and 300 °C. The RF power was varied from 100 W to 200 W in steps of 50 W. This chapter discusses the substrate temperature and the RF power dependent structural, surface morphological, compositional, thermal, optical and electrical characterization results of Cd$_2$SnO$_4$ films. A detailed structural investigations has been performed using the PANalytical X'Pert PRO multipurpose diffractometer with Cu $K_{\alpha}$ radiation ($\lambda = 1.5418$ Å) as a function of substrate temperature and the RF power. The structural properties of the as prepared Cd$_2$SnO$_4$ films were confirmed with the
high resolution transmission electron microscope (HRTEM) and the selected area electron diffraction (SAED) patterns obtained from the Hitachi 8100 electron microscope operating at 200 keV. Surface morphological studies were carried out on the films by JSM 35 CF JEOL scanning electron microscope (SEM) and with the Veeco digital instruments DI-II atomic force microscope (AFM). Raman analysis were done using the Renishaw invia Raman microscope. Optical properties of the films were studied with the Ocean optics HR-2000 fiber optic UV-Vis-NIR spectrophotometer, Varian Cary Eclipse fluorescence spectrophotometer and indigenously integrated Photoacoustic spectrometer. Thermal properties of the films were studied with the photoacoustic spectrometer. Finally the electrical characterizations were done on the samples using the Keithley 2000 Digital multimeter with a linear four probe arrangement and Ecopia Hall effect measurement system Model number HMS-3000. Obtained results are systematically analyzed and compared with the available reports on Cd$_2$SnO$_4$ films.

5.2 Thickness of the sputtered Cd$_2$SnO$_4$ films

As the thickness of the films plays a major role on the physical properties of the films, it is necessary to measure the thickness of the films. Thickness of the films can be controlled by several sputtering parameters such as RF power, Substrate temperature ($T_s$) and target to substrate distance. In the present study, target to substrate distance is optimized with thickness distribution function of the sputtering source which is surrounded with permalloy shield and kept at a constant value of 6 cm. The films were deposited by varying the substrate temperature and the RF power. The thickness of the deposited Cd$_2$SnO$_4$ films was measured using the Mitutoyo SJ-301 surface roughness tester and are found to be in the range of 0.4 to 1 μm.

5.2.1 Effect of substrate temperature and RF power on film thickness

The variation of film thickness with the substrate temperature for different RF sputtering power was shown in Fig. 5.1(a). The film thickness decreases with the increase in the substrate temperature for the films coated at the RF power of 100 W and 200 W. As the substrate temperature increases from the Room temperature (RT) to 300 °C, the particle ejected from the target gains energy from the substrate heating - a physical vapor deposition (PVD) parameter. Hence the adatoms have been cooled down
slower as a result of increasing substrate temperature. It causes the diffusion of the atoms into the film surface and so the reduction in the film thickness. For the films coated at 150 W RF power, on increasing the substrate temperature from RT to 200 °C, the increased sputtering yield of the target material directly reaches the substrate with reduced collisions with the sputtering gas – Argon atoms. But for the films coated at 300 °C, the substrate temperature effect dominates and reduce the thickness for the films coated with the RF power of 150 W.

Figure 5.1(a) and 5.1(b) clearly depicts the effect of RF power that affects the film formation processes. Whenever the RF power is 100 W, the energy of incident Ar ion is itself reduced which causes reduction in sputtering yield and also the film thickness. As the RF power increases from the 100 W to 150 W, the sputtering yield increases as a result of increased ion energy. Probably, sputtered atoms will arrive at the substrate without collision with the sputtering gas molecules. Hence, the film thickness increases for 150 W, as shown in Fig. 5.1(b). When the RF power increases further, say 200 W, sputtered atoms largely collide with the sputtering gas molecules. This increases the mean collision frequency ($v_{ij}$) between the sputtered atoms and the sputtering gas molecules, which is related to the mean free path of the atoms by the relation [1]:

$$\lambda = \frac{c_i}{v_{ij}} \ldots..$$

(5.1)

where, $c_i$ is the mean velocity of the sputtered atoms. The reduced mean free path causes the number of atoms that reaches the substrate. Hence the valley decrease in thickness for 200 W RF power.

### 5.3 Structural studies on Cd$_2$SnO$_4$ films

Need of structural characterization in thin films plays a major role for better device performances. RF magnetron sputtered Cd$_2$SnO$_4$ films can be amorphous or crystalline, depending on the preparative conditions. The degree of crystallinity, structural order and the structural transitions are the parameters which depends on the preparation method and also the deposition parameters. Hence the structural characterization plays a vital role on the material characterization. X-Ray diffraction is a suitable tool, playing the main role on the structural characterization of materials. But in X-ray diffraction pattern of thin films, contribution from substrate to the diffraction can sometimes
overshadow the contributions from the film. If X-ray diffraction recording is adopted to get the small enough penetration depth, the X-ray diffraction should make it possible to characterize the thin films [2]. High resolution transmission electron microscope (HRTEM) images with selected area electron diffraction (SAED) is also used to structurally characterize the RF magnetron sputtered Cd$_2$SnO$_4$ films, in the present study.

5.3.1 X-Ray diffraction analysis

5.3.1.1 Effect of substrate temperature

The conventional X-ray diffraction patterns of the RF magnetron sputtered Cd$_2$SnO$_4$ films on glass substrates at various substrate temperature, using RF power 100 W and 150 W are showed in Fig. 5.2 and Fig.5.3, respectively. The XRD patterns of the films deposited using the RF power of 200W at the substrate temperatures of RT, 100 °C, 200 °C and 300 °C are as shown in Fig. 5.4. The XRD analysis shows that the film coated on glass substrate maintained at RT is in its first state of crystallization or amorphous. It may be due to the incomplete formation of the Cd$_2$SnO$_4$ species on substrate at the lower substrate temperature. The small hump present in the diffraction data at 23.4° is due to the glass substrate. The peak search confirmed a strong peak is presented at 32.3° with the full width at maximum (FWHM) of 3.99° and one very weak peak at 56.18° with the FWHM of 4.0. The search match analysis was done with PDF-4+2008 using the profile and peak data (which is based on the Lebail algorithm) of the patterns of the films deposited at 100 °C, 200 °C and 300 °C in the PANalytical X’Pert Highscore show that the films are having cubic spinel phase (JCPDS card number 01-080-1469) with the highest score and mean deviation of 0.041 Å of \( d \)-spacing. It suggests that the films prepared at 100 °C, 200 °C and 300 °C are crystalline in nature. It is in good agreement with the results of Wang et al. [3]. The film coated at substrate temperature 300 °C is highly oriented along (3 1 1) plane [4] of cubic spinel phase, with the mean deviation of 0.032 Å of \( d \)-spacing. It may be due to the complete film coalescence followed by the perfect growth alignment of the particles on the substrate at higher substrate temperatures.

The intensity of the (3 1 1) peak is plotted against the substrate temperature which is shown in Fig. 5.5. The intensity of the (3 1 1) plane peak is increasing with the
substrate temperature. It may be due to the increased crystallinity of the films with the substrate temperature. It is well known that the diffusion and the hopping distances are dependent on the substrate temperature. Therefore, the diffusion of adatoms on the surface of the films during the film growth process increases as a result of substrate temperature and their diffusion became larger [5]. Hence the crystal quality of the films increases.

The FWHM value of 3.99° with the increased intensity (nearly 700 counts with respect to the background) of the XRD pattern leads to suspect for an integral peak with individual peaks positioned at 32.3° may be 27.47°, 32.3° and 33.81° peaks of the cubic spinel phase. The peak present at 56.18° may be due to integral intensity of the peaks at 51.73°, 56.18° and 59.56°. For confirmation, XRD pattern of the films coated at RT, 100 °C, 200 °C using the RF power 200 W were pattern decomposed to analyze the integrated intensity of the peaks.

For the films deposited at 100 °C and 200 °C, in addition to the peak at ~31.87°, there are some other peaks which are relatively intense. To understand the counterpart of all the peaks, the XRD patterns of the film deposited at 100 °C and 200 °C were analyzed with the whole pattern decomposition by peak by peak fitting procedure [2] considering some of the peaks are partially overlapped. The extracted individual peak pattern of XRD of the Cd₂SnO₄ film is shown in Fig. 5.6. The extracted peaks were used for the cell search using the NTREOR software and matched with the JCPDS card number 04-008-2919, with the mean deviation of 0.03° of interplanar spacing $d$. The cell search revealed that the films are of orthorhombic structure having the refined cell parameters of $a = 3.905$ Å, $b = 11.170$ Å and $c = 3.265$ Å with the cell volume of 142.43 Å³ (Figure of merit $M(20) = 61$). The $hkl$ values were assigned to all the peaks and are shown in Fig. 5.6. However the film deposited at the substrate temperature of 300 °C is highly oriented cubic spinel in nature having the peak intensity of 1575 counts. XRD results shows that the films deposited at the lower substrate temperatures i.e., RT, 100 °C and 200 °C were orthorhombic in nature while the film deposited at 300 °C was cubic spinel in nature preferentially oriented along (3 1 1) plane with very low FWHM value of 0.0358° and a (4 4 0) peak. It indicates that there is a structural phase transition occurs in between the substrate temperature of 200 °C and 300 °C. The crystallite size calculated for the film deposited at the substrate temperature of 300 °C is
Abrutis et al. [6] reported that the Cd$_2$SnO$_4$ film deposited at 400 °C substrate temperature through spray pyrolysis is having pure cubic spinel phase with predominantly oriented peak (3 1 1) and (2 2 0), (4 0 0), (5 1 1) and (4 4 0). Zhao et al. [7] obtained (2 2 2), (4 0 0) and (4 4 0) peaks in the XRD data for CTO prepared at 250 °C. Wohlmuth et al. [8] reported that all of the as-deposited CTO films exhibited a polycrystalline nature displaying a prominent diffraction peak at 2θ = 32.8°, corresponding to (2 2 2) crystal plane. A diffraction peak at 2θ = 38.0° corresponding to the (4 0 0) crystal plane, was observed for substrate deposition temperatures of 200 °C and 300 °C. Enoki et al. [9] obtained only (2 2 2) and (4 0 0) peaks in the XRD data for the CTO films deposited at substrate temperature of 50 °C, 200 °C and 300 °C. At a substrate temperature of 400 °C, they observed the formation of peaks corresponding to Cd$_2$SnO$_4$ phase. Wang et al. [10] the cubic structure for Cd$_2$SnO$_4$ films prepared at 200 °C substrate temperature and further annealed at 400°C at Argon atmosphere for 40 min, modify the peaks preferentially oriented along (3 1 0).

### 5.3.1.2 Effect of RF power

It is inferred from the Fig. 5.2, Fig. 5.3 and Fig. 5.4 that all the Cd$_2$SnO$_4$ films deposited with lower RF power, say 100 W, are in its first state of crystallization, whereas the films coated at higher RF power (except RT) were polycrystalline in nature. When the RF power increases, the crystallinity of the films increase, which may be due to increased surface atom diffusion during sputtering. Furthermore, the RF power also modify the film growth rate [11]. Hence the increase in crystallinity may be due to the decrease in the deposition rate which may be resulted from the collision of sputtered atoms with the Ar ions. The effect of RF power on the intensity of (3 1 1) peak is shown in Fig. 5.7. Intensity of (3 1 1) peak increases with RF power except for the films deposited at RT. It suggests that the crystalline ordering could be localized and hence the films having increased crystalline nature due to the increase in the RF power.

Miyata et al. [12] reported that films deposited at the deposition rate of 40 Å per min are amorphous in nature whereas the films deposited at the film growth rate of 20 Å per min showed the Cd$_2$SnO$_4$ phase with (0 0 1) and (1 3 0) peaks.
5.3.2 Transmission electron microscopic analysis for structural studies
The microstructure of the Cd$_2$SnO$_4$ film deposited with 200 W RF power and 300 °C substrate temperature was confirmed with the high resolution transmission electron microscopy (HRTEM) coupled with selected area electron diffraction (SAED) pattern. The film was peeled off from the substrate and subjected to the HRTEM analysis. The HRTEM micrograph and the SAED pattern of the Cd$_2$SnO$_4$ film is shown in Fig. 5.8 and Fig. 5.9. An ordered lattice fringes can be seen clearly with the interplanar spacing of about 0.274 nm, consistent with the (3 1 1) reflection plane of cubic spinel Cd$_2$SnO$_4$. The extent of the lattice fringes to the upper right side of the micrograph indicates that there is a high degree of perfection with in individual grains of the film. SAED pattern shows that the Cd$_2$SnO$_4$ films are polycrystalline in nature with (3 1 1) and (4 4 0) plane reflections. The HRTEM micrograph and the SAED pattern confirms the excellent quality Cd$_2$SnO$_4$ films that can be deposited at the substrate temperature of 300 °C.

5.4 Surface morphological analysis
Surface morphological studies plays another major role in the field of transparent conducting oxides (TCOs). Surface resistance of the TCOs depends on its thickness. Hence the deposited films should be uniform in nature. Furthermore, the surface of TCOs must be smooth to prevent the localized field effect and surface scattering [13]. In order to explore the suitability and stability of the transparent conducting Cd$_2$SnO$_4$ films, the surface morphological analysis is essential. Hence the surface morphological studies of the Cd$_2$SnO$_4$ films were carried out by JSM 35 CF JEOL scanning electron microscope (SEM) and Veeco digital instruments DI – II atomic force microscope (AFM). The detailed results of the analyzes are discussed elaborately in the following sub-sections.

5.4.1 Scanning electron microscopic analysis
As scanning electron microscope (SEM) is capable of providing information relating to topographical features, morphology, phase distribution, crystal structure and crystal orientation, the surface morphology of the RF magnetron sputtered Cd$_2$SnO$_4$ thin films was analyzed by it. The SEM images were obtained for the films deposited with 200 W RF power at the substrate temperature of RT, 100 °C, 200 °C and 300 °C and for the films coated at 300 °C with RF power 100 W and 150 W to study the variation of...
surface morphology of the films with respect to the substrate temperature and RF power.

5.4.1.1 Effect of substrate temperature
The surface morphological images of Cd$_2$SnO$_4$ films deposited on glass substrates at the substrate temperature of RT, 100 °C, 200 °C and 300 °C with RF power of 200 W are shown in Fig. 5.10. The SEM image of the Cd$_2$SnO$_4$ film deposited at room temperature (Fig. 5.10(a)) is having uniform smooth surface, indicating the amorphous nature of the films as revealed from the XRD results. The film deposited at 100 °C is having a smooth and netted surface with randomly distributed grains over the film surface (Fig. 5.10(b)). Well textured patterns are obtained in the SEM micrographs of Cd$_2$SnO$_4$ films deposited at higher substrate temperatures of 200 °C and 300 °C (Fig. 5.10(c) and (d)). The images shows well shaped discrete nano sized grains homogeneously distributed all over the surface of the films mainly due to the switch over from coalescence stage to the perfect growth nature. At higher substrate temperatures, the diffusion of adatoms will be greater leading to the larger rate of atoms forming a grain. Further, at higher temperature, the films are influenced by thermal gradient, low stress and shocks result the formation of a ordered settlement of crystallites in their preferred sites inside the film structure to form a continuous film. Wang et al. [10] reported the identical morphology for the films deposited with the substrate temperature of 200 °C and further annealed at 400 °C for 40 min. Andrew et al. [14] reported that the SEM images with discrete grains of wide ranges of grain sizes on the film surfaces deposited by chemical vapor deposition. It is noted from the morphological study by SEM, the surface uniformity, crystallinity and homogeneity increase with increasing substrate temperature. The variation in the surface morphology with the substrate temperature indicates that the crystalline nature of the films improves with the substrate temperature which support the XRD results.

5.4.1.2 Effect of RF power
The SEM micrographs of the Cd$_2$SnO$_4$ films deposited at the substrate temperature of 300 °C with various RF power i.e., 100 W, 150 W and 200 W are shown in Fig. 5.11. The films deposited with the lowest RF power 100 W is amorphous which is inferred from the smooth and netted surface in the SEM image (Fig. 5.11(a)). As seen in Fig.
5.11(b), the film deposited with the RF power of 200 W, the film is in the transition stage from the coalescence to perfect growth nature with the effect of RF power. Hence the grains with diffused structure is observed on the surface of the film. Identical structure was reported by Wang et al. [10] for the film deposited at RF power 100 W-400 W at the substrate temperature of 200 °C. The film deposited at RF power 200 W shows well crystallized, nano sized and homogeneously distributed grains, which indicates the high crystallinity of the films deposited at increased RF power.

5.4.2 Atomic force microscopic study
The morphology of the films was also studied by atomic force microscopy (AFM). The advantage of AFM is its capacity to probe the minute details related to individual grains and inter-grain regions as well in three dimensional forms. Since the conduction mechanism is mainly depends on the grain and grain boundary conduction, the analysis plays the vital role. The surface nature of the films has been analyzed with respect to the substrate temperature and also the RF power. The AFM analysis was done for the films deposited at the substrate temperatures of RT, 100 °C, 200 °C and 300 °C with the RF powers of 100 W, 150 W and 200 W.

5.4.2.1 Effect of substrate temperature and RF power
The AFM images of Cd2SnO4 films prepared on glass substrates with the RF power of 100 W, 150 W and 200 W are shown in Fig. 5.12, Fig. 5.13 and Fig. 5.14 respectively. Figure 5.12 shows the AFM surface morphology and the lateral force microscopic (LFM) images of the films deposited at (a) T, = RT, (b) 100 °C, (c) 200 °C and (d) 300 °C with RF power 100 W. The AFM images of the films deposited at room temperature (Fig. 5.12(a)) revealed the formation of the smooth surface which may be due to the amorphous nature of the films. With increasing substrate temperature, the neighboring Cd2SnO4 particles tend to coalescence to form the matrix which can be inferred from Fig.5.12(b). Further increase in temperature shows the complete coalescence of the particles (Fig. 5.12(c)). The films deposited at 300 °C is uniform with nano grains.

Figure 5.13 shows the AFM surface morphology and the LFM images of the films deposited at (a) T,=RT, (b) 100 °C (c) 200 °C and (d) 300 °C with RF power 150 W. Figure 5.13 shows the AFM and LFM images of the Cd2SnO4 films deposited at RT,
100 °C, 200 °C and 300 °C with RF power 200 W. The AFM images for the films deposited with 150 W and 200 W are identical in nature. At lower substrate temperature, the film formation is mainly due to the coalescence of the neighboring particles. When the substrate temperature increases to 100 °C, formation of netted surface with the accumulation of small grains were observed. The films deposited at the substrate temperature of 200 °C are uniform with nano grains distributed all over the surface. Mamazza et al. [15] reported the identical morphology for the Cd$_2$SnO$_4$ films deposited and further annealed at 600 °C in He atmosphere. They have reported the surface roughness as 1.4 nm for the polycrystalline films prepared in the above said conditions. In the present study, the surface roughness was 1.5 nm for the films deposited at the RF power of 150 W and was 1.7 nm for the film deposited at 200 W, which were consistent with the aforementioned value of surface roughness. Wu et al. [16] also reported the polycrystalline Cd$_2$SnO$_4$ films with the surface roughness of 1.3 nm. The films deposited at the substrate temperature of 300 °C were having near spherical shaped grains distributed over the polycrystalline surface of the films which clearly supports the XRD results of the films deposited at the substrate temperature of 300 °C.

The variation in the surface morphology of films is mainly due to the nucleation kinetics which is caused by the substrate temperature and the increase in RF power. At lower deposition temperatures, few nuclei are formed by the lower energy available. The lower nucleation density is visible in the AFM micrographs. However, many nuclei are formed during high-energy depositions and the grains grown by the continuous diffusion of adatoms, leads to the variations in the surface morphology. Further, at higher substrate temperatures, the supersaturation near the surface will be less and hence the critical size of the nucleus and also the size of the stable nucleus will be larger and at the same time the surface diffusion of adatoms will be greater leading to a larger rate of atoms joining the critical nuclei [17].

### 5.5 Compositional analysis

The compositional analysis of the RF magnetron sputtered Cd$_2$SnO$_4$ films were studied in detail by X-ray photoelectron spectroscopy (XPS) or Electron spectroscopy for chemical analysis (ESCA). XPS is a widely used analytical surface-sensitive technique
for investigating the chemical composition of thin solid films. The qualitative XPS survey scan analysis of the Cd$_2$SnO$_4$ films have been obtained in 0 eV–1000 eV Binding Energy ($E_B$) range. The survey scan information is useful, particularly in the identification of the elements present at the film surface. The quantitative XPS scan was used to analyze the cationic ratio of the Cd$_2$SnO$_4$ films. The qualitative and quantitative analysis of the RF magnetron sputtered Cd$_2$SnO$_4$ films were studied in detail with AlK$_\alpha$ radiation at 1.486 keV using ESCA 2000 spectrometer. The Cd$_2$SnO$_4$ films deposited with the RF power 100 W, 150 W and 200 W and at the substrate temperatures of RT, 100 °C and 300 °C were subjected to the XPS analyzes.

5.5.1 Effect of Substrate temperature and RF power

The XPS survey scan spectra of the Cd$_2$SnO$_4$ films prepared at the substrate temperature of (a) RT, (b) 100 °C and (c) 300 °C for various RF power is shown in Fig.5.15(a), Fig.5.15(b) and Fig. 5.15(c). The XPS core level spectra of the Cd$_2$SnO$_4$ films prepared at the substrate temperature of (a) RT, (b) 100 °C and (c) 300 °C for various RF power is shown in Fig.5.16(a), Fig.5.16(b) and Fig. 5.16(c). From the XPS spectra, the RF magnetron sputtered Cd$_2$SnO$_4$ films seems pure without contamination, since there is no any impurity peaks other than the characteristic peak of Cd and Sn. This reveals the compositional purity and the quality of the Cd$_2$SnO$_4$ films. The binding energies were corrected to compensate for any charge induced shifts by setting the C 1s peak 284.6 eV. The measured binding energies of Cd 3d$_{5/2}$, Cd 3d$_{3/2}$, Sn 3d$_{5/2}$, Sn 3d$_{3/2}$ and O 1s peak values are in agreement with the literature [8, 18] values.

Close observation of relative peak intensity and area under the peak of Sn 3d peaks with respect to Cd 3d peak and area, also the peak shift of Sn 3d$_{5/2}$ explain the effect of substrate temperature on the compositional properties of the films. The cationic ratio of the films was calculated using the Cd 3d$_{5/2}$ and the Sn 3d$_{5/2}$ peaks, using the relations

$$R = \frac{C_{Sn}}{C_{Cd}}$$

where,

$$C_{Cd} = \frac{A_{Cd} I_{Cd}}{A_{Cd} I_{Cd} + A_{Sn} I_{Sn}}$$
$$C_{Sn} = \frac{A_{Sn} I_{Sn}}{A_{Cd} I_{Cd} + A_{Sn} I_{Sn}}$$

$A_{Cd}$, $A_{Sn}$, $I_{Cd}$, $I_{Sn}$ are the area of the Sn.
3d\textsubscript{5/2}, Cd 3d\textsubscript{5/2} peaks respectively and I\textsubscript{Sn}, I\textsubscript{Cd} are the Atomic sensitivity factors of Sn 3d\textsubscript{5/2} and Cd 3d\textsubscript{5/2} respectively. The value of I\textsubscript{Sn} and I\textsubscript{Cd} are 3.2 and 2.55, respectively for the corresponding 3d\textsubscript{5/2} peaks. The cationic ratio (Sn/Cd) and the peak position of Cd 3d\textsubscript{5/2}, Cd 3d\textsubscript{3/2}, Sn 3d\textsubscript{5/2}, Sn 3d\textsubscript{3/2} and O 1s peaks are tabulated in Table 5.1. The cationic ratio in Cd\textsubscript{2}SnO\textsubscript{4} films coated with 100 W RF power shows a decrease with increase in the substrate temperature. But for the films deposited at 150 W and 200 W, the cationic ratio shows a similar fashion regardless of the films deposited at RT. The ratio of Sn/Cd increases with increasing substrate temperature, which indicates that the near stoichiometric Cd\textsubscript{2}SnO\textsubscript{4} films can be prepared at the substrate temperature of 300 °C with the RF power of 200 W.

Table 5.1 Binding energies of Cd, Sn, O and cationic ratio obtained from the XPS analysis

<table>
<thead>
<tr>
<th>Preparation Conditions</th>
<th>Binding Energy (eV)</th>
<th>Ratio of Sn/Cd</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Cd 3d\textsubscript{5/2}</td>
<td>Cd 3d\textsubscript{3/2}</td>
</tr>
<tr>
<td>RF Power (W)</td>
<td>Substrate temperature (°C)</td>
<td>405.42</td>
</tr>
<tr>
<td>100</td>
<td>RT</td>
<td>405.73</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>405.75</td>
</tr>
<tr>
<td>150</td>
<td>RT</td>
<td>405.73</td>
</tr>
<tr>
<td>100</td>
<td>405.64</td>
<td>412.34</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>405.82</td>
</tr>
<tr>
<td>200</td>
<td>RT</td>
<td>405.43</td>
</tr>
<tr>
<td>100</td>
<td>405.69</td>
<td>412.36</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>405.61</td>
</tr>
</tbody>
</table>

The peak shift of Sn 3d\textsubscript{5/2}, as inferred from Table 5.1 may be due to the chemical shifts, which is caused by either the change of formal oxidation state of Sn or the local physical and chemical environment [19]. Since the charge induced shifts are compensated by the peak position of C 1s, the peak shift is mainly due to the change in oxidation state of Sn. Since the atoms of a higher positive oxidation state exhibit a higher binding energy due to the extra Coulomb interaction between the photo-emitted
electron and the ion core and the Sn can be present either +2 or +4 oxidation state, the peak shift can be strongly attributed to the oxidation states of Sn. For the formation of ternary \( \text{Cd}_2\text{SnO}_4 \), the Sn should be in +4 oxidation state which has the peak position at 487.2 eV. The peak position at 486.8 eV and 486.73 eV for the films deposited at room temperature with RF power 100 W and 200 W may be attributed to the +2 oxidation state of Sn. It suggests that the formation of pseudo binary cadmium tin oxide films with SnO as its constituent oxide which has the +2 oxidation state of Sn. The shift of peaks to the higher binding energy side and also the cationic ratio of 0.57 confirms the formation of \( \text{Cd}_2\text{SnO}_4 \) at the substrate temperature of 300 °C with 200 W RF power.

The effect of substrate temperature and the RF power on the chemical compositional properties lacks in literature values. Wohlmuth et al. [8] and Fan et al. [18] only reported the compositional analysis of \( \text{Cd}_2\text{SnO}_4 \) films. Wohlmuth et al. [8] reported that the ratio of Sn/Cd increased monotonically from 0.141 to 0.184 as the substrate temperature was increased from 50 °C to 300 °C. But they have not reported the conditions for the preparation of stoichiometric \( \text{Cd}_2\text{SnO}_4 \) films.

5.6 Thermal properties of \( \text{Cd}_2\text{SnO}_4 \) films

Thermal properties like thermal diffusivity, thermal conductivity and the thermal effusivity of transparent conducting oxides (TCO) used in various applications, must be determined very precisely and frequently. The thermal diffusivity is an important physical parameter that determines the heat transport through the material. This may be the essential condition of the proper choice of material and subsequent reliability and durability of the material. Since the thermal diffusivity is the parameter, which depends closely on the microstructural variations, composition and the processing condition of the samples [20], it should be studied precisely. Though much work has been reported on the electrical and optical properties of the material \( \text{Cd}_2\text{SnO}_4 \), to the best of our knowledge, no attempts have been made to understand its thermal properties in addition to the optical properties [4]. Photoacoustic spectroscopy was used to study the thermal and also the optical properties of the transparent conducting \( \text{Cd}_2\text{SnO}_4 \) films. Though the photoacoustic technique has emerged as an important tool for the accurate evaluation of the thermal properties of a large variety of materials, especially semiconductors [21, 22], present report is an attempt to study the thermal property of the transparent
conducting oxides (TCO).

5.6.1 Effect of substrate temperature
The plots of PA phase versus the square root of modulation frequency of the light for Cd$_2$SnO$_4$ thin films deposited at the substrate temperature of RT, 100 °C, 200 °C and 300 °C using 200 W RF power are shown in Fig. 5.17. It is clear from the figure that there is a curvature indicating the presence of thermo elastic bending. Since the thickness of the sample is very low, the pronounced thermo elastic bending is due to the much lower value of the thermal diffusivity of the Cd$_2$SnO$_4$ thin films. The thermo elastic bending is also depends on the degree of crystallinity of the sample [23]. However, since the Rosencwaig-Gersho theory is valid for the thermally thick regime, the curve was fitted to the higher modulation frequency region to obtain the thermal diffusivity for the Cd$_2$SnO$_4$ films deposited at varying substrate temperature with the RF power of 100 W, 150 W and 200 W.

*Table 5.2 Thermal diffusivity of Cd$_2$SnO$_4$ films prepared at various deposition conditions*

<table>
<thead>
<tr>
<th>Preparation conditions</th>
<th>Thermal diffusivity (in $10^{-6}$ m$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Power (W)</td>
<td>Substrate temperature (°C)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>RT</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200</td>
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<td>300</td>
</tr>
<tr>
<td>150</td>
<td>RT</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>300</td>
</tr>
<tr>
<td>200</td>
<td>RT</td>
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<td></td>
<td>100</td>
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<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>300</td>
</tr>
</tbody>
</table>
The thermal diffusivity of the Cd$_2$SnO$_4$ thin films coated at room temperature (RT), 100 °C, 200 °C and 300 °C and with the RF power of 100 W, 150 W and 200 W were calculated through the photoacoustic spectroscopy with the mean accuracy of ±0.0032×10$^{-7}$ m$^2$/s. The calculated thermal diffusivity is tabulated in Table 5.2 and is shown graphically in Fig. 5.18 as a function of the substrate temperature for various RF power. Since, no other experimental data of thermal diffusivity ($\alpha$) are available in the literature for Cd$_2$SnO$_4$ thin films [4]; we cannot compare our results with others. The photoacoustic depth profiling measurements given away that the thermal diffusivity increases with increase in substrate temperature except for the films deposited at 100 W RF power. The increase in the thermal diffusivity with the substrate temperature may be due to the increase in the degree of crystallinity of Cd$_2$SnO$_4$ thin films [4]. As the crystallinity of the films increasing with the substrate temperature, there may be a decrease in lattice distortion [24]. This further pronounces decrease in phonon scattering that results the increase in the thermal diffusivity of the samples. But for the films deposited at 100 W RF power, the reverse trend is observed which may be due to the increase in phonon scattering.

5.6.2 Effect of RF power

The variation of thermal diffusivity of Cd$_2$SnO$_4$ films as a function of RF power at various substrate temperatures is as shown in Fig. 5.19. As the RF power increases, the crystalline ordering is localized hence a decrease in lattice distortion in the films deposited at 200 °C and 300 °C. This further pronounces a decrease in phonon scattering that resulting an increase in the thermal diffusivity of the films. Similarity in crystallinity of the films deposited at the substrate temperature of RT shows the constant values of thermal diffusivity which may be inferred from Fig. 5.19 and from the results of XRD.

5.7 Optical characterizations

Thin films absorb and emit electromagnetic radiations. The characteristics of the films frequently manifest themselves in the way it interacts with radiation. The fundamental basis for the interaction varies with the wavelength of the radiation, and the information gained from the films under study normally vary. The interaction further varies with the structural properties of the films. Hence the RF magnetron sputtered Cd$_2$SnO$_4$ films
were subjected to study their structural and optical properties.

5.7.1 Photoluminescence studies
The photoluminescence properties of Cd$_2$SnO$_4$ films deposited on glass substrates at various substrate temperature and RF power were studied and the results are discussed in detail.

5.7.1.1 Influence of Substrate temperature
To study the photoluminescence properties of Cd$_2$SnO$_4$ films as a function of substrate temperature, the films deposited with RF power 200 W at the substrate temperature of RT, 100 °C, 200 °C and 300 °C were subjected to the photoluminescence (fluorescence) spectroscopy. Figure 5.20 shows the photoluminescence spectra of the films deposited at various substrate temperatures. In Fig. 5.20, strong peak observed at about 3.35 eV corresponds to the near band edge (NBE) ultraviolet emission that comes from the free excitonic emission [25]. The relatively weak UV emission at about 3.15 eV may be due to the defects that may trap the photo-generated electrons and/or holes. The deep level emission (DLE) at about 2.96 eV may exist due to the interstitial oxygen ion state.

It was evidenced from Fig. 5.20 that the intensity of the NBE peaks enhanced with the increase of substrate temperatures. It is widely reported that the intensity of the NBE peaks with respect to the DLE peaks has much relationship with the crystal quality, usually the better crystallinity. These results are consistent with the XRD results. Further, we claim that the results of photoluminescence can be related to the thermal diffusivity which is obtained from the photoacoustic spectroscopy. During excitation and emission transitions, interaction with electron and a photon was explored. Also they includes a phonon processes with vibronic coupling between electronic states of the fluorescence center and the phonon energies of the crystal host lattice of the films [26]. Following absorption and excitation at the center site, phonon creation and destruction at the site populates adjacent Stark levels in the excited center. The isolated center can be thought of as interacting with its crystalline environment via the crystal field, which is time-varying because the lattice is vibrating. If the phonon creation and destruction is large, the emission transition mostly result in relaxation processes, without emission [26]. There is a decrease the emission probability of the centers and hence a decrease in emission intensity with increasing phonon creation and
As the crystallinity of the films increasing with the substrate temperature, there may be a decrease in lattice distortion [24]. This further pronounces a decrease in the phonon scattering which may be inferred from the increase of thermal diffusivity values with the increasing substrate temperature. The decrease in phonon scattering causes the phonon creation and destruction in the crystal lattice. Hence, the PL intensity increases with the substrate temperature.

5.7.1.2 Effect of RF power
Figure 5.21 shows the photoluminescence spectra of Cd$_2$SnO$_4$ films for various RF power. It is evidenced from the Fig. 5.21, that the PL intensity increases due to the increase in crystallinity with the RF power which further supports the results of XRD and thermal diffusivity.

5.7.2 Optical transmittance
An elaborate investigation on the optical properties of transparent conducting oxide (TCO) film becomes essential for their effective device oriented applications. Transparent conducting oxides (TCOs) should posses high enough transmittance as their name itself portrays the property. This is well known fact that the optical properties of thin films are highly sensitive to the amorphous content, presence of impurities, voids, dislocations and lattice trapping centers. It is to be noted that for TCO device application, the films must be free from the above mentioned defects. High transmittance of films would automatically mean that the films are free from the above defects. The optical transmittance of Cd$_2$SnO$_4$ films were studied by Ocean optics HR-2000 high resolution fiber optic spectrometer. The films prepared with various RF power and at various substrate temperature were subjected to study the change in optical transmittance with respect to substrate temperature and RF power.

5.7.2.1 Effect of Substrate temperature
The normalized optical transmittance spectra of RF magnetron sputtered Cd$_2$SnO$_4$ thin films at various substrate temperatures (i.e., RT, 100 °C, 200 °C and 300 °C) with 100 W RF power are shown in Fig. 5.22. Figure 5.23 shows the optical transmittance spectra of Cd$_2$SnO$_4$ films deposited with 150 W RF power at various substrate temperatures. Figure 5.24 shows the optical transmittance spectra of Cd$_2$SnO$_4$ films deposited with
200 W RF power at various substrate temperature. The interference fringes present in the transmittance spectra of Cd$_2$SnO$_4$ films deposited with the intentional substrate temperature show that the RF magnetron sputtered Cd$_2$SnO$_4$ films are highly uniform with crystalline quality. The maximum transmittance of 93% in the visible range of spectrum is observed for the films deposited at room temperature with RF power 100 W, 150 W and 200 W. The transmittance values decrease with increasing the substrate temperature to 300 °C for the films deposited at 100 W RF power, which may be due to the increase of crystallization from amorphous nature [27] with increasing substrate temperature. The films deposited at 150 W and 200 W also shows a decreasing trend in the transmittance value except for the films deposited at 300 °C.

The optical transmittance, decreasing with increasing substrate temperature may be further explained with the electronic properties of the n-type heavily doped TCOs. According to this, the decrease in transmittance in the higher wavelength region may be attributed to the increased free carrier scattering (increased plasma frequency) due to the increase in carrier concentration for the films deposited with intentional substrate temperature. For confirmation, the electrical properties of the films also should be checked.

The absorption edge in the transmittance spectra show a variation with the increasing substrate temperature. The absorption edge shifted towards the higher wavelength side (red shift) with increasing substrate temperature for the films deposited with the RF power of 100 W, whereas it is shifted towards the lower wavelength side (blue shift) with increasing substrate temperature except $T_s=RT$, for the films deposited with 200 W. The shift in absorption edge for the films deposited with 150 W RF power shows a random effect with increasing substrate temperature. The shift in the absorption edge is explained in forth coming sections.

5.7.2.2 Effect of RF power
The normalized optical transmittance spectra of Cd$_2$SnO$_4$ films deposited with various RF power is shown in Fig. 5.25. The transmittance of the Cd$_2$SnO$_4$ films is less in the visible region while increasing the RF power for the films deposited at various substrate temperatures. The decreasing trend of optical transmittance with increasing substrate temperature may be due to the increase of crystallization with the increasing RF power.
The absorption edge shift shows a red shift with increasing RF power for the films deposited at RT, 100 °C and 200 °C. The band edge of Cd$_2$SnO$_4$ films deposited at 300 °C with increasing RF power shows a red shift for the RF power 100 W to 150 W. It is shifted to the lower wavelength side while the RF power is 200 W. As the decrease in transmittance for the films deposited at 300 °C with 200 W RF power shows the increase in crystallinity, the shift in band edge to the lower wavelength region may be correlated to the electrical properties of the films.

Wohlmuth et al. [8] reported that the optical transmittance of Cd$_2$SnO$_4$ films was 80 to 85% for the films deposited at the substrate temperature of 300°C with 400 W RF power. Bel Hadj et al. [28], Wang et al. [10] and many coworkers [29-31] reported that the annealed films only has an average optical transmission of about 90%.

### 5.7.3 Optical bandgap

The optical bandgap of the Cd$_2$SnO$_4$ films were determined using the optical absorption spectroscopy. The bandgap values determined is further confirmed with the bandgap values estimated from the photoacoustic spectroscopy.

In order to determine the optical band gap of the films through the optical absorption spectroscopy, the absorption spectra of the films were used. The optical absorption coefficient ($\alpha$) was calculated from the transmittance spectrum using the relation,

$$\alpha(\lambda) = \frac{-\ln(T)}{t}$$

where $t$ is the thickness of the film, $T$ is the optical transmittance.

In order to find the direct band to band transition energies, $(\alpha h\nu)^2$ was plotted against the photon energy. The energy gap can be determined from the intercept of the linear portion of the curve to the zero $(\alpha h\nu)^2$. The plot is often referred to as Tauc plot.

#### 5.7.3.1 Effect of substrate temperature

The Tauc plot ($(\alpha h\nu)^2$ vs $h\nu$) of Cd$_2$SnO$_4$ films deposited at various substrate temperature (RT, 100 °C, 200 °C and 300 °C) with 100 W RF power is shown in Fig. 5.26. The bandgap values varies from 3.49 eV to 3.10 eV, with increasing substrate temperature. This bandgap narrowing is mainly due to the optical band filling which is
enumerated from the crystallization of the films with increasing substrate temperature. The Tauc plot of Cd$_2$SnO$_4$ films deposited with 150 W RF power is shown in Fig. 5.27. The bandgap values of the films deposited with 150 W RF power also decreasing with increasing substrate temperature, except for the film deposited at 200 °C. This widening of bandgap may be due to the well known Moss-Burstein effect [32]. The Tauc plot of Cd$_2$SnO$_4$ thin films deposited at various substrate temperature with 200 W RF power is shown in Fig. 5.28. The Tauc plot of Cd$_2$SnO$_4$ films deposited at the 200 W RF power shows that the bandgap is increasing with the increasing substrate temperature. But for the film deposited at 100 °C shows a significant decrease on optical bandgap. This is due to the noteworthy increase in the crystallinity of the films deposited at 100 °C when compared to the films deposited at RT, which are amorphous, as revealed from the X-ray diffraction and AFM analysis. When the substrate temperature is increased from 100 °C to 300 °C, the bandgap is shifted to the higher energy region. To check the bandgap values and the variation of bandgap values with substrate temperature, the films deposited with 200 W were subjected to photoacoustic spectroscopic analysis.

The photoacoustic spectra of Cd$_2$SnO$_4$ films deposited with 200 W at the substrate temperature of RT, 100 °C, 200 °C and 300 °C are shown in Fig. 5.29. From the origin of the absorption (dips), the optical bandgap values are obtained. The bandgap values estimated from the photoacoustic spectra is tabulated in Table 5.3 and plotted in Fig. 5.30 to compare the values obtained from the PA measurements and from the optical absorption measurements. The bandgap values obtained from the PA spectra exactly matches with the values obtained from the optical absorption spectroscopy.

**Table 5.3 Bandgap values of Cd$_2$SnO$_4$ thin films deposited at 200 W RF power**

<table>
<thead>
<tr>
<th>Substrate temperature (°C)</th>
<th>Bandgap values estimated from optical absorption spectroscopy (eV)</th>
<th>Bandgap values estimated from Photoacoustic spectroscopy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>3.32</td>
<td>3.37(1)</td>
</tr>
<tr>
<td>100</td>
<td>3.07</td>
<td>3.09(2)</td>
</tr>
<tr>
<td>200</td>
<td>3.21</td>
<td>3.21(1)</td>
</tr>
<tr>
<td>300</td>
<td>3.30</td>
<td>3.29(1)</td>
</tr>
</tbody>
</table>
The observed change of the optical band gap energy with substrate temperature can be partially explained on the basis of the density of states model proposed by Mott and Davis [33]. Accordingly, the width of the localized states near the mobility edges depend on the degree of disorder and defects present in the materials. The presence of high concentration of localized states in the band structure is responsible for the low values of energy gap. The reduction in the number of defects decreases the density of localized states in the band structure, consequently increasing the optical band gap. According to this, the film processed at 300 °C has less density of localized states and therefore exhibits high optical band gap compared to other films.

The increase in bandgap or bandgap widening (blue shift) could be explained on the basis of Moss-Burstein effect for the $n$-type heavily doped TCOs. According to Segev et al. [34], when the system is n-type doped, the optical transition can occur between the conduction band minimum (CBM) and the states with energy higher than the CBM energy, for k points away from the Brillouin zone center, due to the partial filling of the conduction band which shifts the fermi energy level above the conduction band minimum. The energy of the transition between the CBM and the second conduction band (SCB) decreases with increasing carrier concentration. This causes the transparency of the films, since transparency of the good performing TCO depends on the energy separation between the CBM and SCB. Our results show an increase in optical bandgap with the substrate temperature, which may be due to the Moss-Burstein effect, believing that there is an increase in the carrier concentration with the increasing substrate temperature. Our results make evident the theoretical predictions of Segev et al. [34] that the Moss-Burstein shift as a results of transition from valence band to unoccupied conduction states, away from the Brillouin zone center, causes an increase in optical bandgap, when measured by the optical absorption spectroscopy and also by photoacoustic spectroscopy [4].

### 5.7.4 Optical constants

The variations in refractive index $n$ and extinction co-efficient $k$ as a function of wavelength in weak absorption region for the Cd$_2$SnO$_4$ film deposited at different substrate temperature (RT, 100 °C, 200 °C and 300 °C) with the RF power 150 W and 200 W were observed and its variation shown in Fig. 5.31 and Fig. 5.32, respectively.
The rise and fall in the extinction co-efficient is due to the variations in the absorbance. The extinction co-efficient also varies between 0.001 and 0.06 in the wavelength range 400 nm - 1000 nm. The refractive index of Cd$_2$SnO$_4$ films is calculated using the Swanepoel method [35] and the refractive index value is almost constant in the visible region (1.6 – 2.4) for all the films. Obtained values are slightly higher in the UV region and attain the lowest value in the IR region.

5.8 Electrical properties

The electrical properties of the transparent conducting oxides plays a vital role, since the device performance is mainly depends on its electrical parameters like resistivity ($\rho$), carrier concentration ($n$) and the mobility of the charge carriers ($\mu$). The resistivity measurements of Cd$_2$SnO$_4$ thin films were studied with Keithley 2000 digital multimeter with linear four probe arrangement and the Hall effect studies were done using the Ecopia Hall effect system model number HMS-3000 with 0.57 T. The electrical behavior of the Cd$_2$SnO$_4$ thin films were elaborately studied and the results are presented in this sub-section.

The hot probe test results revealed that the Cd$_2$SnO$_4$ films are $n$-type semiconductor which is also confirmed with the Hall effect measurements. The temperature dependance of resistivity (plot of 1000/T vs $ln(\rho)$) of Cd$_2$SnO$_4$ films deposited at different substrate temperature (RT, 100 °C, 200 °C and 300 °C) with the RF power of 100 W, 150 W and 200 W are shown in Fig. 5.33, Fig. 5.34 and Fig. 5.35, respectively. The Room temperature resistivity values are tabulated in Table 5.4. The Cd$_2$SnO$_4$ films deposited with 200 W at 300 °C is having very low resistivity of $3.192 \times 10^{-4}$ Ωcm which is the lowest value ever attained for the as-prepared Cd$_2$SnO$_4$ films prepared by sputtering. Wohlmuth et al. [8] reported that the resistivity was dropped from $3.3 \times 10^{-3}$ Ωcm to $1.1 \times 10^{-3}$ Ωcm as the substrate temperature increased from 50 °C to 300 °C. Many coworkers [28, 29, 36] have reported the same range of lowest resistivity for the Cd$_2$SnO$_4$ films after the post heat treatment only. The figures show that the Cd$_2$SnO$_4$ films deposited with 150 W and 200 W RF power and at the substrate temperature of 200 °C and 300 °C appear to be degenerate in the temperature range 295 K to 395 K. Further, the resistivity of the films is decreasing with increasing substrate temperature which may be due to the increase in carrier concentration [37].
The carrier concentration and mobility values obtained from the Hall effect measurements were tabulated in Table 5.4 along with the mean free path of electrons. The carrier concentration value is well agreed with the reported value and the mobility of the film deposited at 300 °C substrate temperature is within the theoretical limit [38]. The carrier concentration is increasing with substrate temperature except for the film deposited at 300 °C with 150 W RF power. The increase of carrier concentration with the increasing substrate temperature may be due to the creation of oxygen vacancies with the removal of interstitial oxygen providing more donor states [39-41]. The mobility of the films shows a decreasing trend with increasing substrate temperature.

**Table 5.4 Electrical parameters of Cd$_2$SnO$_4$ thin films deposited for various preparation conditions**

<table>
<thead>
<tr>
<th>Preparation conditions</th>
<th>RF Power (W)</th>
<th>Substrate temperature (°C)</th>
<th>Carrier concentration (cm$^3$)</th>
<th>Mobility (cm$^2$/Vs)</th>
<th>Resistivity (Ωcm)</th>
<th>Mean free path (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>RT</td>
<td>2.53×10$^{17}$</td>
<td>243.1</td>
<td>0.148</td>
<td>3.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>3.006×10$^{17}$</td>
<td>238.8</td>
<td>0.086</td>
<td>3.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>4.008×10$^{17}$</td>
<td>217.4</td>
<td>0.071</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>1.624×10$^{19}$</td>
<td>19.39</td>
<td>0.019</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>RT</td>
<td>2.349×10$^{17}$</td>
<td>481.1</td>
<td>0.055</td>
<td>6.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>4.362×10$^{16}$</td>
<td>501</td>
<td>0.285</td>
<td>3.59</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>4.388×10$^{20}$</td>
<td>35.7</td>
<td>3.985×10$^{-4}$</td>
<td>5.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>9.094×10$^{19}$</td>
<td>97.67</td>
<td>7.028×10$^{-4}$</td>
<td>8.94</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>RT</td>
<td>1.4×10$^{19}$</td>
<td>63.52</td>
<td>0.007</td>
<td>3.11</td>
<td></td>
</tr>
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<td>2.407×10$^{19}$</td>
<td>59.78</td>
<td>0.004</td>
<td>3.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>3.531×10$^{20}$</td>
<td>39.38</td>
<td>4.489×10$^{-4}$</td>
<td>5.66</td>
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<tr>
<td></td>
<td>300</td>
<td>6.337×10$^{20}$</td>
<td>30.86</td>
<td>3.192×10$^{-4}$</td>
<td>5.39</td>
<td></td>
</tr>
</tbody>
</table>

According to Wohlmuth et al. [8], as the substrate temperature increases, the mobility should be increased due to the reduction in grain boundary scattering and/or a decrease in impurity scattering. To determine whether a reduction in grain boundary scattering is the main mechanism responsible for the enhancement of mobility, the mean free path of the electrons was determined by Wohlmuth et al. using the formulation,
\[ l_e = \left( \frac{h}{2e} \right) \left( \frac{3n}{\pi} \right)^{\frac{1}{13}} \mu \] 

But the mobility is decreasing with increasing substrate temperature in the present study. This result is in agreement with the results suggesting that the grain boundary scattering should be insignificant in TCO films based on alternative, carrier mean free path arguments [42-45]. This may be due to that the scattering time for the slow growth films is significantly larger. Hence the reduction in the mobility which is inferred from Fig. 5.36 is mainly due to the increase in the carrier concentration with grain boundary conduction is not a dominant process, since the mean free path in decreasing with increasing substrate temperature for the films deposited with 100 W RF power whereas it is increasing for the films deposited at the RF power of 200 W.

The increase in carrier concentration with the substrate temperature for the films deposited with 200 W RF power confirms that the blue shift observed in the bandgap with the increasing substrate temperature is mainly due to the increase in carrier concentration of the films.

5.9 Conclusion
In this chapter, a detailed description is given about the structural, surface morphological, compositional, thermal, optical and electrical properties of RF magnetron sputtered Cd$_2$SnO$_4$ thin films. Extra-mural studies are also extended towards various factors such as substrate temperature and RF power, which influence the above characteristic properties of Cd$_2$SnO$_4$ films. Correlation studies among these properties of the material are also discussed. The characteristic parameters of the films that are extracted from these studies are also tabulated.
References


(2004).


