Chapter 4

Preparation and Characterisation of Copper Indium Selenide Absorber Layer
The key component of the solar cell is the polycrystalline absorber film. The heterojunction is formed between the p-type absorber film and the n-type layer. The efficiency of a solar cell depends mainly on the amount of incident light absorbed by the material. This device characteristic is determined by the crystal structure and characteristics of the absorber layer.

The essential characteristics of a typical absorber layer are, it should

- Be p-type
- Possess high absorption coefficient
- Have good carrier life time
- Have direct band gap
- Be non toxic
4.1 Introduction

Current emphasis in photovoltaic is directed towards the development of high performance inexpensive solar cells that can serve in the long term as viable alternatives to the single crystal silicon technology. Foremost among those materials that have emerged as leading candidates are the I-III-VI$_2$ and II-IV-V$_2$ group semiconductors based solar cells. Of the I-III-VI$_2$ group that are of particular interest are CuInX$_2$ (X = S, Se, Te). Among the variety of CuInX$_2$ materials interest in CuInSe$_2$ (CIS) dates back to the work of Wagner et al [1]. It has proven to be a promising absorber material for high efficiency photovoltaic devices since it possesses the following useful properties (i) it has a direct band gap about 1.02 eV at room temperature, which is in the energy range for optimum solar conversion; (ii) it can be doped easily either n or p type by varying the Cu/In ratio and thus permits the formation of homo junctions and several types of hetero junctions; and (iii) it has high quantum efficiency and good thermal stability [2]. But the photovoltaic interest in CuInSe$_2$ and related compounds is mainly due to the extremely high absorption coefficient, possessed by these materials (Fig. 4.1). This high value of $\alpha$ ($10^5$ cm$^{-1}$) implies that 99% of the incoming photons are absorbed within the first micrometer of the material. As a result, only about 1$\mu$m of this material is required to effectively absorb all the incoming photons and hence reduce the consumption of raw materials. The material properties can be varied by replacing part of the indium by gallium and/or part of the selenium by sulfur to form Cu(In,Ga)(S,Se)$_2$ [3].

Interest in CIS based solar cells considerably increased with the report of 10% efficient cells in 1982 by three source evaporation [4]. Conversion efficiencies
higher than 19.2% have been achieved using these materials [5] until this date. CIS-based solar cells are very stable, and thus their operational lifetimes are long. CIS-based thin films can be prepared both from gas and liquid phases by a variety of methods.

![Absorption spectrum of CuInSe2 compared with other photovoltaic semiconductors](image)

Figure 4.1 Absorption spectrum of CuInSe2 compared with other photovoltaic semiconductors [6].

4.2 Material Properties of CuInSe2

4.2.1 Crystallographic Structure

CuInSe2 is a member of the family of I-III-VI2 (ABX2) chalcopyrite semiconductors. The ABX2 chalcopyrite crystal structure resembles the zinc-blende structure in that each of the two cations A and B are coordinated tetrahedrally by four anions X (Fig. 4.2), but the anion is coordinated by 2A+2B,
with generally dissimilar neighbourhood bond lengths $R_{AX} \neq R_{BX}$. The unit cell is thus tetragonal [7]. The primitive cell for this structure is made up of eight tetrahedrons with shared vertices, so that the whole cell is just two stacked cubic structures. By convention, the short edge is labelled $a$ and the long edge is labelled $c$.

![Figure 4.2 Chalcopyrite crystal structure](image)

In CuInSe$_2$, each group I (Cu) or group III (In) atom has four bonds to the group VI atom (Se). In turn each Se atom has two bonds to Cu and two to In. The tetrahedral structure becomes distorted due to differing bond strength between I-VI and III-VI atoms. Hence the ratio of the lattice constant $c/a$ is not exactly two. It varies from 2.01 to 1.96. For CuInSe$_2$, the lattice parameters are, $a = 0.5789$ nm and $c = 1.162$ nm. The different bond strengths make the anion (Se)
to adopt an equilibrium position close to any one pair of the cation than to other, causing anion displacement and the unequal bond length.

### 4.2.2 Phase Diagram

The phase diagrams of CuInSe₂ have been extensively investigated by Godecke et al. [8]. The phases for the Cu-In-Se system are represented either by ternary phase diagrams or pseudo binary phase diagrams. Pseudo binary representations were chosen to simplify presentation, since the system in question tends to exist along pseudo binary tie lines. The figure 4.3 shows the pseudo binary phase diagram for the Cu-In-Se system.

According to this phase diagram, four different phases are likely to occur in this ternary system. They are: the alpha phase (CuInSe₂), the beta phase (CuIn₃Se₅), the delta phase (the high temperature sphalerite phase) and Cu₂S. The phase adjacent to the alpha phase has a similar structure. The beta phase is actually a defect chalcopyrite phase build by ordered arrays of defect pairs.

At room temperature alpha phase extend from a Cu content of 22% to 24.5%. Thus the range of copper percentage for a single phase CuInSe₂ is very small not even 25% of Cu. For efficient thin film solar cells the Cu content varies between 22 and 24%. This range lies within the single phase region of the alpha phase at the temperature 500 – 550°C. At room temperature it lies in the alpha + beta region. Thus there is a tendency for phase separation in CuInSe₂ after deposition.

Although phase diagram shows a relatively small range for single phase CuInSe₂, the partial replacement of In with Ga as well as the use of Na containing
substrates considerably widens the single phase region. The Ga is able to diffuse by a vacancy mechanism through either Cu or In vacancies, the addition of Ga to pure CuInSe₂ increases the band gap [10].

4.2.3 Optical and Electrical Properties

The performance characteristics of polycrystalline CuInSe₂ materials are highly dependent on their stoichiometric composition, defect chemistry and structure which in turn are strongly related to the film growth parameters. They are also critically influenced by the presence of secondary phases in the bulk of the material. The following sections deal with how these parameters affects the properties of CuInSe₂ thin films.

CuInSe₂ thin films possess band gap energy equal to 1.1 eV. Early measurements of the band gap of single crystalline CuInSe₂ exhibited nominal
disagreements [11], suggesting a value in the range of 1.02 to 1.04 eV [12]. Optical characterisation of polycrystalline CuInSe₂ absorber films, suitable for devices, almost always indicates a significantly lower effective band gap of approximately 0.9 eV [13]. These variations in the optical properties of CuInSe₂ materials are a direct consequence of variations in stoichiometry. Intragranular vacancies have also been shown to affect the optical band gap [14].

The studies of Rockett et al [15] have shown the presence of secondary phases and segregated layers on the surface of polycrystalline films grown by physical vapor deposition changes the conductivity in the order of magnitude. The presence of secondary phases at grain boundaries also causes sub band gap absorption [16]. It has been reported that an additional absorption other than the main absorption edge [17] due to the secondary impurity phases such as Cu₇S contribute at energies below band gap as well as transitions from acceptor levels to the conduction band.

The variation of absorption coefficient with the In/Cu ratio has been studied [18]. The indium rich films had high energy gaps. They explained it as, when In/Cu ratio increases, indium occupies some of the copper sites, resulting antisite defects. Since the size of the indium atom is larger than that of copper, this effect would lead into an increase in band gap. There is also report that, the samples having lower In/Cu ratio would absorb low energy photons more effectively than those having higher In/Cu ratio [19].

Electrical properties of CuInSe₂ thin film depend strongly upon the stoichiometry, preparation methods, and substrate temperature during deposition of the films. When the Se content is low, the films show p-type and low conductivity for high Cu/In ratio, and n-type and high conductivity for low
Cu/In ratio. For high Se content, the film show p-type but larger conductivity for high Cu/In ratio, while n-type and smaller conductivity for low Cu/In ratio [20]. The resistivity of CuInSe₂ can be varied from $10^2$ to $10^4 \, \Omega \, \text{cm}$ depending on the Cu/In ratio and the preparation conditions [21]. In situ conductivity measurements during the growth of CuInSe₂ films have been carried out by Alt et al [22]. It was found from the $\sigma$ vs. $1/T$ plot that for In rich films, a formation of band bending occurs at grain boundaries.

4.2.4 Effect of Temperature

The formation of a thin p-type MoSe₂ layer between the Mo and the absorber that occurs during the absorber preparation at sufficiently high temperatures [23, 24] is found beneficial for the cell performance for several reasons. First, it forms a proper ohmic back contact. The Mo/CuInGaSe₂ contact without the MoSe₂ layer is not ohmic but a Schottky type contact that causes resistive losses [25]. The second advantageous consequence of the MoSe₂ interface layer is improved adhesion of the absorber to the Mo back contact. Another advantage is, since the band gap of MoSe₂ is wider (about 1.4 eV) than that of a typical CuInSe₂ absorber, it reduces recombination at the back contact, providing simultaneously a low-resistivity contact for holes [26]. The MoSe₂ layer also prevents further reactions between CuInGaSe₂ and Mo.

A moderate inter diffusion of CdS and CuInSe₂, which occurs to some extent at high annealing temperature [27] is potentially beneficial to the cell performance. Guillen and Herrero have identified a variable range hopping conduction mechanism taking place at very low temperatures and a thermally activated conductivity over the grain boundaries at temperatures close to the room
temperature. The heat treatment of the films involves an increase in the conductivity and a decrease in the thermal activation energy [28].

A detailed study on phases formed during the production of CuInSe₂ grown by reacting the stalked layers of Cu, In and Se were carried out by Sachan et al [29]. They obtained the elemental phases of In and Se with the phases of CuSe₂ and Cu₁₁In₉ for low reaction temperature. But temperature above 215°C the peak corresponding to Se was observed in the XRD pattern. At temperature 235°C and above CuInSe₂ appeared as the main peak in the XRD pattern and single phase CuInSe₂ obtained at reaction temperature of 400°C.

Detailed study on the evaporation temperature on properties of the film prepared by vacuum evaporation was explained in the work of Isomura et al [30]. For application as an absorber layer in a high efficiency solar cell, a CuInSe₂ film needs to have a long diffusion length and long minority carrier life time. Large grain size, uniform morphology and non existence of a second phase are required for this purpose. Kim et al have reported that the film obtained by selenization of Cu/In precursors at low vacuum satisfied these conditions [31].

4.3 Various Deposition Methods for CuInSe₂ Thin Film Preparation

The success of photovoltaic energy conversion depends on the availability of low cost, large area solar cell modules. Recent progress was achieved by the systematic investigations and optimization of the basic production processes of different technologies. Varieties of methods have been experimented to grow CuInSe₂ thin films like molecular beam epitaxy [32], flash evaporation [33], multi-source evaporation [34], single-source evaporation [35], RF sputtering [36],
spray pyrolysis [37, 38], electrodeposition [39], and selenization of metallic film [40-45].

CuInSe₂ film formation can be divided mainly into two major categories (1) those where Se is incorporated with the metals during material delivery (2) processes where the metals are delivered separately from Se. Co evaporation, electrodeposition, sputtering etc are included in the first category while the second one indicates the two stage process which involves deposition of the precursor metal and subsequent reaction with selenium to produce CuInSe₂.

Sputtering offers simple and flexible control over film stoichiometry. Characterisation of CuInSe₂ films prepared by sputtering has been reported by He et al [46].

On the basis of economic considerations, preparation of CuInSe₂ by electrodeposition seems attractive. Electrodeposition of CIS-based thin films has been studied extensively by several groups [47, 48] since 1983 when Bhattacharya published the first paper on one-step electrodeposition of CuInSe₂ thin films [49]. The films prepared by this method in general revealed a microcrystalline or amorphous phase with widely differing stoichiometry. The studies of Chaure and co workers showed that the conversion from p type to n type conductivity varies as deposition cathodic voltage increased from low to high values [50].

Vacuum deposition has its merit of simplicity of preparation. Evaporation processes can be applied to CuInSe₂ growth. Evaporation by two sources, evaporation by three sources and the two stage process are the some of the thermal evaporation techniques used for the growth of CuInSe₂ thin films. The two stage process and the evaporation by three sources have certain advantages.
over other techniques in terms of stoichiometry control, hence preferred nowadays. The most successful absorber deposition method for high efficiency small-area devices seems to be the three-stage co evaporation of \( \text{CuInSe}_2 \) from elemental sources in the presence of excess Se vapor [51]. However, poor material utilization and the difficulty of obtaining uniform material fluxes over large area substrates are some of the concerns related to scaling this method to a high production level [52]. So recent research are going on the development of a relatively easily scalable two stage deposition technique, to produce uniform coatings of thin films on large area substrates.

The two stage process which includes the selenization of precursors such as Cu/In alloy [53] also offers great advantages in terms of low cost of production. This technology forms the basis for commercial products now being developed by Siemens Solar Technologies. The potentials for large area compositional uniformity and control of the ratio of Cu/In by thermal evaporation followed by selenization results in \( \text{CuInSe}_2 \) films suitable for solar cell application [54].

A solar cell fabricated with absorber layer grown by two stage process has attained an efficiency of 9.8% [55]. For the production of \( \text{CuInSe}_2 \) by two stage method, the detailed investigations of phase formation process in Cu-In bilayers have been reported in literature. Cu-In alloys are known to exist in different phases and compositions ranging from pure copper to pure indium [56]. The deposition of single phase precursor is not possible by sequential evaporation of the metals. The heating up of the film is necessary for diffusion reactions leading to the formation of \( \text{CuIn}_2 \), \( \text{Cu}_{11}\text{In}_9 \) and at higher temperature \( \text{Cu}_7\text{In}_3 \) [57].
4.4 Experimental Details

CuInSe$_2$ thin films were made by cost effective two stage process. Two stage process involves deposition of Cu-In precursors in the first step followed by their selenization using H$_2$Se gas or Se vapour in the second stage. In this technique, both steps, the precursor preparation and the selenization, are important for the quality and the adherence of the CuInSe$_2$ film onto substrate. Selenization of the Cu-In precursors have utilized H$_2$Se gas or Se vapour. The use of H$_2$Se gas has been considered environmentally unfriendly due to its toxic nature [58]. In addition, there are problems relating to rapid volume expansion leading to poor adhesion of the film onto the Mo back contact, and In loss resulting from the complexity of reaction kinetics that is the interdiffusion of intermediate phases which leading to poor quality films. Hence, in this work, selenization was achieved using elemental Se.

4.4.1 Preparation of Cu$_{11}$In$_9$ Alloy

For the preparation of the CuInSe$_2$ (CIS) by two-stage process, the first step is the preparation of Cu$_{11}$In$_9$ precursors. It is achieved by the annealing of Cu-In bilayers in vacuum. Cu-In bilayer was deposited on glass and Mo substrates by thermal evaporation in high vacuum chamber at a pressure of $3 \times 10^{-6}$ mbar. High purity metals of copper (99.99%) and indium (99.999%) were evaporated from molybdenum boats. The thickness of the In layer was maintained at 400 nm and that of Cu layer varied to obtain various Cu/In ratios. Both depositions were carried out at room temperature. The deposition rate and thickness of individual layers were carefully controlled and measured using an oscillatory quartz crystal monitor located at a position close to the substrate. The film obtained after
selenization was found to be less adhesive. So for better adhesion of CIS, a thin layer of gallium of thickness 10 nm was deposited prior to indium deposition.

The Cu-In bilayer thin films thus prepared were annealed at different temperatures varying from $153^\circ C$ to $200^\circ C$ in high vacuum of $3 \times 10^{-6}$ mbar for 2 hours. The optimum temperature found was $153^\circ C$. The choice of this temperature is based on the phase diagram (Fig. 4.4) of Cu-In by Subramanian et al [59]. The annealing temperature below $153^\circ C$ resulted in incomplete reaction while temperature above $153^\circ C$ resulted in loss of indium.

![Figure 4.4 Cu-In binary phase diagram](image)

Figure 4.4 Cu-In binary phase diagram
4.4.2 Chalcogenisation

In the second stage, the precursors were removed from vacuum and exposed to an atmosphere of selenium using N₂ as carrier gas in a horizontal quartz tube provided with a specially designed furnace, which allowed rapid heating and cooling of samples. A thermal cycle consisting of rapid heating and cooling of samples was selected for selenization since the slow heating and cooling cycle had been resulted in indium loss. The Se granules were used as the selenium source since the H₂Se gas is toxic. The Se granules were heated separately and N₂ gas is passed through the chamber to carry the selenium vapour to the reaction zone. The complete details of the selenization system are described in the chapter 2. The selenization was carried out for different duration such as 1, 2 and 3 hours. The structural studies were performed for optimising the reactive annealing time for the formation of single phase CuInSe₂ film. After optimising the duration of selenization, studies on the effect of annealing temperature were studied. The selenization temperature at the reaction zone was varied from 250° C to 400° C. The other parameters like duration of selenization and heating profiles were kept constant. The temperature was monitored by a thermocouple attached to the furnace. After optimising the selenization temperature and duration of selenization as 350° C and 3 hours respectively, the experiments were repeated using precursor of various Cu/In ratios.

Crystallinity of the prepared alloys and films were measured using X-ray diffractometer with Cu-Kα radiation. The surface morphology and composition of the films were evaluated using the scanning electron microscopy (SEM) technique and energy dispersive X-ray spectroscopy (EDX) respectively. Optical transmittance measurements have been performed using UV-VIS-NIR
spectrophotometer. The electrical properties of the films were investigated by current–voltage measurements.

4.5 Results and Discussions

4.5.1 Structural Characterisations

Structural characterisation of the Cu-In precursors was carried out using XRD. The Cu-In alloy deposited over glass, molybdenum and the gallium coated molybdenum substrates were analysed.

Figure 4.5 shows the XRD pattern of the Cu-In precursor layer grown over glass, molybdenum and gallium coated molybdenum substrates. All the major
peaks can be indexed to that of Cu$_{11}$In$_9$ which indicating a good mixing of elemental species. For Cu-In deposited over glass the main reflection was from (312) plane. For Cu-In grown over Mo the grains were randomly oriented showing reflections from (312) and (112) planes. When a thin layer of gallium was introduced between Molybdenum and Cu-In layer, major reflection peak in the XRD was that from (511) plane of Cu$_{11}$In$_9$ alloy.

Figure 4.6 Surface morphologies of (a) Mo/CuIn, (b) Mo/Ga/CuIn
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The SEM results shows that the CuIn alloy on Mo are consisted of a smooth surface. The size and number of particles changed when gallium layer is introduced prior to the Cu and In bilayers (Fig. 4.6).

The XRD patterns of samples selenized at 350° C for different duration of 1, 2 and 3 hours are studied in detail (Fig. 4.7). It is known from the studies performed by Agnihotri et al, Szot et al and Don et al that the diffraction patterns of CuInSe₂ polycrystalline thin films having chalcopyrite structure have peaks at 26.6, 27.8, 35.6, 42, 44.4, 52.5, and 71 for 2θ and these peaks correspond respectively to the reflections from the (112), (211), (105)/(203), (220)/(224), (116)/(312), and (316) planes [60-62]. It was seen from the diffraction pattern of sample selenized for 3 hours that the peaks 27, 35.85, 42.15, 44.45, 52.75 and 71.7 were observed here too. The other samples formed by selenization for 1 hour and 2 hours also showed similar XRD spectra. But for the samples selenized for 1 hour, some peaks of Cu₁₁In₉ and In₂Se₃ binary peak were identified in addition to CuInSe₂ phase. When the duration of selenization was increased to 2 hours, then the In₂Se₃ peak was not and CuInSe₂ peak (200) was observed. Single-phase CuInSe₂ thin films were obtained for samples selenized for 3 hours at 350° C. In all the three cases, the dominant peak corresponds to (112) plane of CuInSe₂. From these results it was concluded that the CuInSe₂ films formed by selenization of metallic precursors had the chalcopyrite structure. The presence of Cu/In alloy and In₂Se₃ phases in the samples selenized for 1 hour and 2 hours indicates that for short duration the reaction is incomplete. The optimized selenization duration was 3 hours to obtain crystalline single phase CuInSe₂ film.
The experiment carried out by varying the selenization temperature but for fixed duration of 3 hours. Figure 4.8 - 4.11 shows the XRD pattern of films prepared for different selenization temperature ranging from 250°C to 400°C.
Figure 4.8 XRD pattern of CIS film grown from Cu$_{11}$In$_9$ precursors selenized at 250º C. (Θ and Δ indicate the XRD pattern corresponding to Cu$_{11}$In$_9$ and In$_2$Se$_3$ phases respectively).

Even at the selenization temperature as low as of 250º C CuInSe$_2$ peaks were detected. But binary phases like Cu$_{11}$In$_9$ and In$_2$Se$_3$ were also present (Fig. 4.8). An identical sample selenized at 300º C showed Cu$_{11}$In$_9$ phase, along with CuInSe$_2$. The presence of other binary phases like Cu$_3$Se$_2$ and In$_2$Se$_3$ were also detected (Fig. 4.9). This might be due to the fact that at 300ºC the precursor starts to decompose and indium is free to evolve as In$_2$Se$_3$ and Cu$_3$Se$_2$ [63]. The lower selenium vapor pressure and the higher temperature might be favouring the growth of binary phases of selenium.
Figure 4.9 XRD pattern of the CIS film prepared from Cu$_{11}$In$_9$ precursors selenized at 300°C. ($\Theta$, $\Delta$ and $\Xi$ indicate the XRD pattern corresponding to Cu$_{11}$In$_9$ In$_2$Se$_3$ and Cu$_3$Se$_2$ phases respectively).

The samples selenized at 350°C resulted in crystalline quality material with no detectable evidence of secondary phases (Fig. 4.10).

The main reflection corresponds to that from (112) plane; which are closed packed planes in the chalcopyrite lattice. The usual growth direction of thin films is perpendicular to these planes [64].
Figure 4.10 XRD pattern of the CIS film prepared from Cu$_{11}$In$_9$ precursors selenized at 350$^\circ$C.

When selenization temperature was raised to 400$^\circ$C, some impurity phases such as Cu$_3$Se$_2$, In$_2$Se$_3$, CuSe$_2$ were detected in X-ray diffraction patterns (Fig. 4.11). The presence of binary phases Cu$_3$Se$_2$, In$_2$Se$_3$ and CuSe$_2$ can be attributed to the segregation of In away and Cu towards the upper part of the layer at such a high temperature [65]. The optimum selenization temperature for the formation of single phase CuInSe$_2$ is found to be 350$^\circ$C. Binary phases coexist at above and below this selenization temperature.
Figure 4.11 XRD pattern of CIS film prepared from Cu$_{11}$In$_9$ precursors selenized at 400$^\circ$C. (Θ, Δ and Ξ indicate the XRD pattern corresponding to Cu$_3$Se$_2$, In$_2$Se$_3$ and CuSe$_2$ phases respectively).

SEM and EDX studies showed that the sample with nearly stoichiometric starting precursors (Cu/In = 1.041) are homogeneous with round shaped structures. The films which are Cu rich samples (Cu/In = 1.2) were characterised by poor morphological properties, having no apparent grain.
Figure 4.12 SEM micrographs demonstrating the structural features of samples selenized at 350°C for 3 hours using precursor having Cu/In ratio a) 1.2 b) 1.04 c) 0.73.
structure. The visual appearance of indium rich films (Cu/In=0.73) suggests an outer rough surface made of clusters (Fig.4.12).

4.5.2 Optical and Electrical characterisations

The absorption coefficient ($\alpha$) of the CuInSe$_2$ films was calculated from the absorption spectra. Estimates of the sizes of band gap were obtained by plotting $(\alpha h\nu)^2$ vs. $h\nu$ and extrapolating the linear portion near on set of absorption to the energy axis. The intercept gives the energy.

The variation of the band gap of CIS films with different selenization temperature was also studied. It was observed that the band gap increases with increasing selenization temperature (Fig. 4.13). As the selenization temperature increases from 250$^0$ C the band gap is found to increase and at selenization temperature 400$^0$ C the band gap is 1.16 eV. The prepared films have a band gap of 1.05eV at a selenization temperature of 350$^0$ C, which is close to the theoretical band gap suitable for solar cell [66]. These films were single phase CuInSe$_2$ as indicated by XRD data. The low value of band gap compared to the bulk at lower selenization temperature may be attributed to the presence of secondary phases. At higher selenization temperatures comparatively less secondary phases were observed. The increase in band gap at higher selenization temperature (400$^0$ C) may be due to the presence of binary phases as evident from the XRD patterns.
Resistivity of the samples was determined using two-probe method using silver electrodes in planar geometry. The resistivity was in the order of $10^{-2}$ $\Omega$ cm.

The type of the majority carriers in the present study was determined by hot-point probe method and all the samples were found to be p-type.

### 4.6 Conclusions

CuInSe$_2$ thin films were grown by a cost effective two stage process which includes the thermal evaporation of metallic bilayers followed by selenization. Single-phase CuInSe$_2$ with (112) preferred orientation was obtained at a selenization temperature of 350$^\circ$C for 3 hours selenization. The presence of some binary phases in films for shorter selenization period and lower
selenization temperature may be due to the incomplete reaction and indium loss. The CuInSe₂ thin films prepared under the optimum condition of selenization temperature of 350°C and reaction time 3 hours showed optical band gap energy of 1.05 eV and a resistivity of 10² Ω cm. The CIS films grown by two stage process can be used for the fabrication of solar cells.
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