

## IMPACT OF Cu INCORPORATION TO THE CdTe THIN FILM PROPERTIES FOR PHOTOVOLTAIC APPLICATION

K. S. RAHMAN<sup>a</sup>, K. A. ARIS<sup>b</sup>, M. R. KARIM<sup>c</sup>, M. O. AIJAZ<sup>c</sup>, M. A. DAR<sup>c</sup>,  
M. A. SHAR<sup>c</sup>, H. MISRAN<sup>a</sup>, N. AMIN<sup>a\*</sup>

<sup>a</sup>*Institute of Sustainable Energy, Universiti Tenaga Nasional (@The National Energy University), Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia*

<sup>b</sup>*Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, The National University of Malaysia, 43600 Bangi, Selangor, Malaysia*

<sup>c</sup>*Center of Excellence for Research in Engineering Materials (CEREM), Deanship of Scientific Research, King Saud University, Riyadh 11421, Kingdom of Saudi Arabia*

Cadmium Telluride (CdTe) thin films were deposited on cleaned soda lime glass substrates at 300°C by RF magnetron sputtering technique. Thin films of Cu were subsequently deposited on top of CdCl<sub>2</sub> treated CdTe thin films for 2 min, 5 min, 10 min and 15 min corresponding to a thickness of 20 nm, 50 nm, 90 nm and 120 nm, respectively by sputtering at a substrate temperature of 200°C. CdTe and Cu stacks were annealed at 200°C for 15 minutes in a vacuum furnace. The influence of different Cu concentration on the structural, topographical, optical, electrical and morphological properties of sputtered CdTe thin films were then investigated by XRD, AFM, UV-Vis, Hall Effect measurement and FESEM, respectively. From the XRD analysis, a sharp CdTe peak corresponding to the (111)<sup>cub</sup> plane at 2θ=23.8° and a low intensity Cu<sub>2</sub>Te peak representing (200)<sup>cub</sup> reflection plane at around 2θ=24.8° were found for different Cu growth time on CdTe. There was no existence of Cu<sub>2</sub>Te peak when Cu was deposited on top of CdTe for 2 min. The relative peak intensity was higher for 10 min Cu growth on CdTe. Significant changes were observed in the films surface roughness due to the different Cu concentration. The average and RMS roughness values showed rising trend for higher Cu concentration. The band gap values remained around 1.50 eV for all the films. Electrical measurements showed p-type conductivity and highly degenerate semiconducting behavior with highest carrier concentration of (7.5x10<sup>18</sup> cm<sup>-3</sup>) as achieved for 10 min of Cu growth. Some preliminary CdTe based photovoltaic devices were also fabricated without any process or structural optimization, where the highest photovoltaic conversion efficiency of 3.77% (V<sub>oc</sub> = 0.42 V, J<sub>sc</sub> = 26.4 mA/cm<sup>2</sup> and Fill Factor = 0.34) was obtained for the CdTe films having 50 nm thick Cu layer deposited on top.

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**Keywords:** Photovoltaic materials; CdTe thin films; sputtering; deposition time; Cu concentration.

### 1. Introduction

The exploration of a viable photovoltaic solar cell technology that can compete with conventional fossil fuels has recognized CdTe based thin film solar cell as a feasible substitute to attain the expected low-cost photovoltaic device. Among group II–VI compound semiconductors; CdTe is one of the most promising semiconductor materials in thin film solar cells. With its commercial success, CdTe has become a key thin film photovoltaic technology and is drawing an augmented attention from both scientific and commercial perception.

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\*Corresponding author: sajed\_cuet\_eee@yahoo.com

Thin film CdTe based solar cells are regarded to be the foremost photovoltaic materials for its low cost, easier deposition, high optical absorption coefficient and high chemical stability. CdTe has a direct band gap of around 1.5 eV, which is very near to the ideal value for the efficient photo conversion [1-5]. One of the challenging issues for CdTe solar cell is the deposition of a good ohmic contact to CdTe. A low contact resistance is obligatory for good performance and long term stability [6]. However, it is challenging to realize ohmic contact to p-CdTe partly because it has a high work function of 5.7 eV, which is higher than that of most common metals [7]. A metal with a work function  $> 5.7$  eV is needed to form an ohmic contact on p-type CdTe. Since such metals are not available, the typical approach to surmount the naturally existing Schottky barrier is to create a heavily p-type doped CdTe surface by chemical etching [8, 9] and apply a buffer layer of high carrier concentration between CdTe and the metal. This permits a useful band alignment that lessens the barrier width at the back contact interface.

Cu thin films have broad applications in electronic devices owing to both high electro migration resistance and high electrical conductivity [10]. Therefore, Cu thin films are extensively exploited for many applications such as diodes [11], solar cells [12] and high-speed integrated circuits (IC) [13]. Copper in elemental form (such as Cu/Au back contacts) or as dopant in other material (such as Cu doped ZnTe) is being utilized for the stable back contact of CdTe solar cells [15, 16]. To form an ohmic contact to CdTe, a small amount of Cu is usually incorporated to dope the CdTe surface [17]. Copper is accountable for at least four consequences within CdTe devices: 1) Assists to form a low-resistance back contact 2) dope the CdTe [14], 3) enhance the minority carrier lifetime in CdTe [15], and 4) cause degradation to the devices. Generally, efficient back contacts have been attained by applying a thin layer of Cu on the Te rich surface [16]. After an annealing process, an intermixed  $\text{Cu}_x\text{Te}$  degenerated semiconductor layer is formed and Cu diffuses into the CdTe bulk material, where it behaves as an acceptor-like dopant [14, 17]. However, copper has been recognized to diffuse swiftly through CdTe, mostly through grain-boundaries to the underlying CdS layer [16]. This diffusion eventually degrades the cell performance, mainly long-term stability [16]. Therefore, the supply of Cu should be minimized while the ohmic characteristic of p+ CdTe contact is considered [16].

The exploitation of cuprous telluride ( $\text{Cu}_2\text{Te}$ ) has emerged immensely in recent years as a stable back contact in CdTe based heterojunction and tandem solar cells [17].  $\text{Cu}_2\text{Te}$  offers low valence band offset with CdTe [17, 18], which ultimately maximizes the hole current between the CdTe layer and the back contact. It also enlarges p-type doping by diffusion of Cu and Te [17, 20]. Doping a polycrystalline CdTe is challenging and is normally achieved using Cu as a dopant with several fabrication methods [20]. Hence, the main purpose of this work was to deposit Cu on top of CdTe thin film by sputtering and then anneal to form  $\text{Cu}_2\text{Te}$  layer which would be beneficial for CdTe thin film solar cells fabrication. The impact of Cu concentration on the performance of CdTe thin films has also been investigated in detail for photovoltaic application.

## 2. Experimental Details

In this study, RF magnetron sputtering has been utilized which is a very popular physical vapor deposition (PVD) system for depositing thin films with beneficial optical and electronic properties and precise surface morphology. This method is very supportive for fabricating compound and metallic thin films for broad range of applications [19]. RF magnetron sputtering technique has many benefits, such as high purity and homogeneity of the films; high adhesion and high precision of thickness control or grain size of the grown films, the prospect of large area deposition and low cost, etc. [20].

Before sputtering, the chamber pressure was pumped down to a base pressure of  $1 \times 10^{-5}$  Torr. CdTe thin films were sputtered on the soda lime glasses for approximately 90-120 min with a deposition rate of around 0.15 - 0.20 nm/sec at substrate temperature of 300°C. The treatment of CdTe samples was done with a soaked solution of 0.3 mole  $\text{CdCl}_2$  in DI water. The  $\text{CdCl}_2$  treated CdTe samples were annealed in a vacuum furnace at 400°C for 15 min. The chamber pressure was reserved in the range 220-250 Torr. The samples were kept in the annealing chamber while waiting the chamber temperature to arrive at room temperature. After that, Cu was sputtered on top

of the CdCl<sub>2</sub> treated CdTe layer at substrate temperature of 200°C. The Cu thin films were deposited with 40-50 watts of RF power. The rate of argon flow was fixed at the values between 3-5 SCCM. The working pressure during sputtering was 3×10<sup>-2</sup> Torr. The depositions were carried out for 2 min, 5 min, 10 min and 15 min, respectively to achieve considerable growth of Cu films on top of CdTe thin films. The typical sputtering conditions are listed in Table 1. Apart from various investigations such as physical, optical and electrical characterizations of the CdTe stacks, some preliminary solar cell devices were also fabricated utilizing these CdTe layers.

Table 1: Typical sputtering conditions of Cu to deposit on top of CdTe thin films

Parameter	Condition
Target	Cu (99.99% pure)
RF Power	40-50 W
Sputtering Gas	Pure argon (3-5 SCCM)
Base Pressure	1 × 10 <sup>-5</sup> Torr
Working Pressure	3 × 10 <sup>-2</sup> Torr
Deposition Time	2, 5, 10 and 15 min
Substrate Temperature	200°C
Cu Film Thickness	20-150 nm

### 3. Result and Discussions

#### 3.1. Structural Properties Analysis by XRD

The structural and crystallographic properties of the Cu deposited CdTe films was analyzed from the X-ray powder diffraction (XRD) data taken by 'BRUKER aXS-D8 Advance Cu-Kα' diffractometer. The lattice parameter 'a' for cubic phase structure [hkl] for the films was then calculated from the Brag's law and Vegard's law [21].

$$d_{hkl} = (\lambda/2) \operatorname{cosec}\theta \quad (1)$$

$$a_{\text{cubic}} = d_{hkl} (h^2 + k^2 + l^2)^{1/2} \quad (2)$$

Where d is the interspacing between the planes in the atomic lattice, λ is the X-ray wavelength (0.15406 nm), θ is the angle between the incident ray and scattering planes and 'a' is the lattice constant. To attain more structural information, the mean crystallite sizes (D) of the films are calculated by using Scherrer formula [22].

$$D_{hkl} = 0.9\lambda/\beta\cos\theta \quad (3)$$

Where θ is the Bragg diffraction angle, λ is the X-ray wavelength (0.15406 nm) and β is the full width at half maximum [FWHM] of the film diffraction peak at 2θ. Crystallinity is tremendously correlated to FWHM values. The deterioration of the films crystallinity is resolved by the higher values of FWHM, whereas the larger crystallite sizes indicate the enhanced crystallinity of the films [23]. The developed microstrain (ε) has been calculated from the following relation [24].

$$\varepsilon = \beta/4 \tan\theta \quad (4)$$

Here, β and θ has their usual significances. The higher value of ε signifies the highly polycrystalline film whereas single crystalline nature symbolizes lower microstrain value. The dislocation density of thin films is calculated by the Williamson and Smallman's relation [25].

$$\delta = n / D^2 \quad (5)$$

Here,  $n$  is a factor, which is considered almost equal to unity for minimum dislocation density and  $D$  is the crystallite size or grain size.

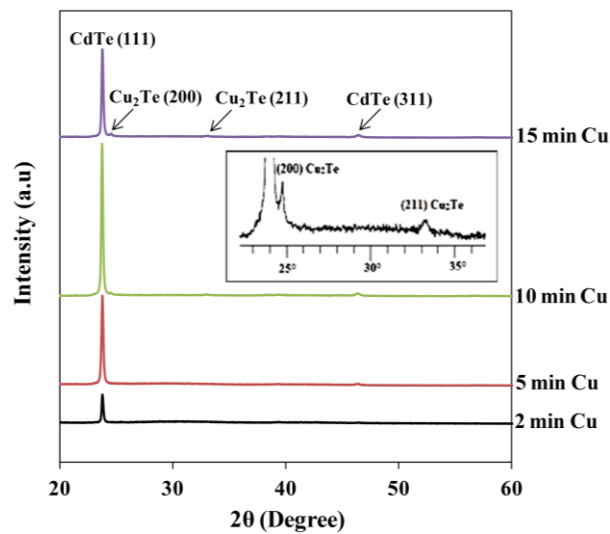


Fig 1. XRD spectra of Cu deposited CdTe thin film for deposition time 2 min, 5 min, 10 min and 15 min.

Fig. 1 illustrates the XRD spectra of Cu deposited CdTe thin film for Cu deposition time 2 min, 5 min, 10 min and 15 min corresponding to Cu thicknesses of 20 nm, 50 nm, 90 nm and 120 nm, respectively. From Fig. 1, it can be seen that the films showed polycrystalline nature with a preferential orientation along the (111) cubic plane of CdTe and found at  $2\theta=23.8^\circ$  for all the deposition times confirming a pure cubic zinc blend structure. Another low intensity diffracted peak was observed belong to CdTe with positions at  $2\theta=46.51^\circ$  correspond to (311) cubic plane. However, when Cu was deposited on top of CdTe for 2 min (equivalent to 20 nm thickness of Cu layer), there was no existence of  $\text{Cu}_2\text{Te}$  peak. The variations in the peak height were obtained for higher Cu deposition times. When the Cu deposition time was varied to 5 min (50 nm), 10 min (90 nm) and 15 min (120 nm), two low intensity diffracted peaks were observed belonging to the  $\text{Cu}_2\text{Te}$  with positions at around  $2\theta=24.8^\circ$  and  $2\theta=33.1^\circ$  corresponding to (200) and (211) hexagonal planes. These diffracted peaks and planes also authenticated the formation of  $\text{Cu}_2\text{Te}$  for 5 min, 10 min and 15 min Cu growth on CdTe which was the key aim of this study. All these diffracted peaks were well matched with the JCPDS (00-015-0770) file; JCPDS (00-057-0477) file and were in good agreement with the literature of CdTe and  $\text{Cu}_2\text{Te}$  cubic structure.

The calculated values for different structural parameters of the Cu deposited CdTe thin films are tabulated in Table 2. The average crystallite sizes have been found in the range of about 40 nm – 290 nm which are considerably large and suitable for photovoltaic applications. Basically, large crystallite denotes less grain boundary which might have negative carrier recombination centers. From Table 2, it was observed that the  $(111)^{\text{cub}}$  phase showed lowest value of crystallite size (40.61 nm) for 15 min Cu deposition time (90 nm thick Cu layer on CdTe) whereas the highest crystallite size (288.37 nm) was found for the  $(311)^{\text{cub}}$  phase for 5 min Cu growth (50 nm of Cu) on CdTe. The lattice constant was found 0.65 nm for all the CdTe diffracted peaks. The lattice constant was obtained around 0.70 nm for  $\text{Cu}_2\text{Te}$  for 10 min (90 nm thick Cu) and 15 min (120 nm thick Cu) Cu deposition time on CdTe. However, the values of microstrain and dislocation densities altered with the variation of Cu deposition times. The highest microstrain of  $0.18 \times 10^{-3}$  was achieved for  $(111)^{\text{cub}}$  CdTe phase for Cu deposition time 10 min and 15 min indicating the highest lattice misfit and dislocation in the film structure. The maximum value of dislocation density  $0.60 \times 10^{11} \text{ cm}^{-2}$  was also attained for the same orientation and same Cu deposition time for Cu thin layer over 90 nm. All these values were in conformity with previous

study and therefore can be helpful for  $\text{Cu}_2\text{Te}$  formation which would eventually contribute for high efficiency CdTe thin film solar cells fabrication [5, 21].

Table 2: Calculated values of the structural parameters of Cu deposited CdTe thin films ( $1.2 \mu\text{m}$ ) for various deposition times

Deposition Time (Cu Thickness)	hkl	$d_{\text{hkl}}$ (nm)	a (nm)	$\beta$ (deg)	$D_{\text{hkl}}$ (nm)	$\epsilon$ [ $\times 10^{-3}$ ]	$\delta$ [ $\times 10^{11}$ ] ( $\text{cm}^{-2}$ )
2 min Cu (20 nm)	(111) CdTe	0.37	0.65	0.12	67.68	0.10	0.22
5 min Cu (50 nm)	(111) CdTe	0.37	0.65	0.17	47.78	0.16	0.44
	(311) CdTe	0.20	0.65	0.03	288.37	0.06	0.01
10 min Cu (90 nm)	(111) CdTe	0.37	0.65	0.20	40.61	0.18	0.60
	(311) CdTe	0.20	0.65	0.05	173.01	0.09	0.03
	(200) $\text{Cu}_2\text{Te}$	0.36	0.72	0.06	135.62	0.06	0.05
	(211) $\text{Cu}_2\text{Te}$	0.27	0.66	0.05	165.6	0.06	0.04
15 min Cu (120 nm)	(111) CdTe	0.37	0.65	0.20	40.61	0.18	0.60
	(311) CdTe	0.20	0.65	0.05	173.03	0.09	0.03
	(200) $\text{Cu}_2\text{Te}$	0.36	0.72	0.05	162.75	0.05	0.04
	(211) $\text{Cu}_2\text{Te}$	0.27	0.66	0.03	276.33	0.04	0.01

### 3.2. Surface Topography Analysis by AFM

Atomic Force Microscopy (AFM) is an essential and fitting tool for studying surface texture of thin films. AFM analysis has been carried out to attain microscopic information on the surface topography, average roughness ( $S_a$ ), RMS roughness ( $S_q$ ) of the grown thin films. Though AFM images are often used as micrographs of the surface, the data are also utilized to quantify surface roughness. The surface topographical effects of Cu on CdTe thin films performance due to the variation of Cu deposition times were observed from AFM images as shown in Fig. 2. Fig. 2 exemplifies the grains (from 2D image) and topography (from 3D image) of Cu deposited CdTe thin films grown by RF magnetron sputtering system for deposition times 2 min, 5 min and 15 min, respectively. The measured average roughness,  $S_a$  and RMS roughness,  $S_q$  for all the films are represented in Table 3.

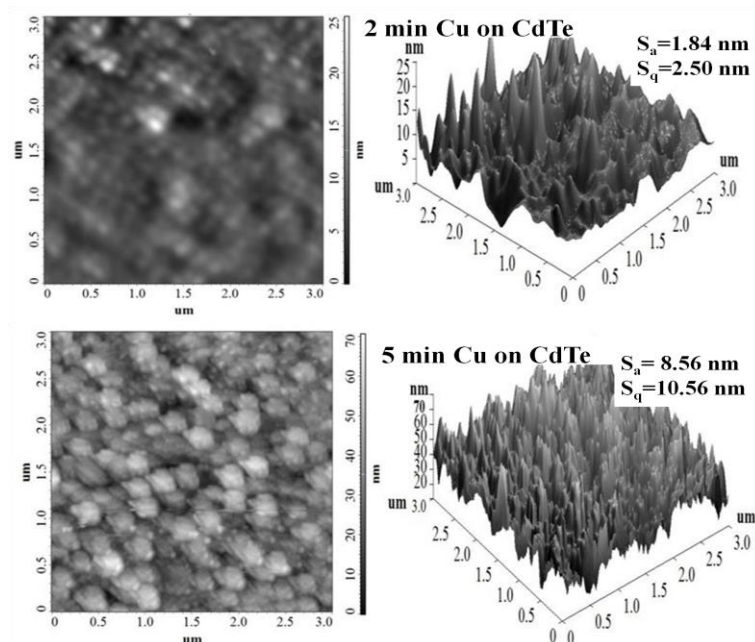


Fig. 2.1. 2D and 3D AFM images for Cu deposited CdTe thin film for deposition times 2 min, 5 min,

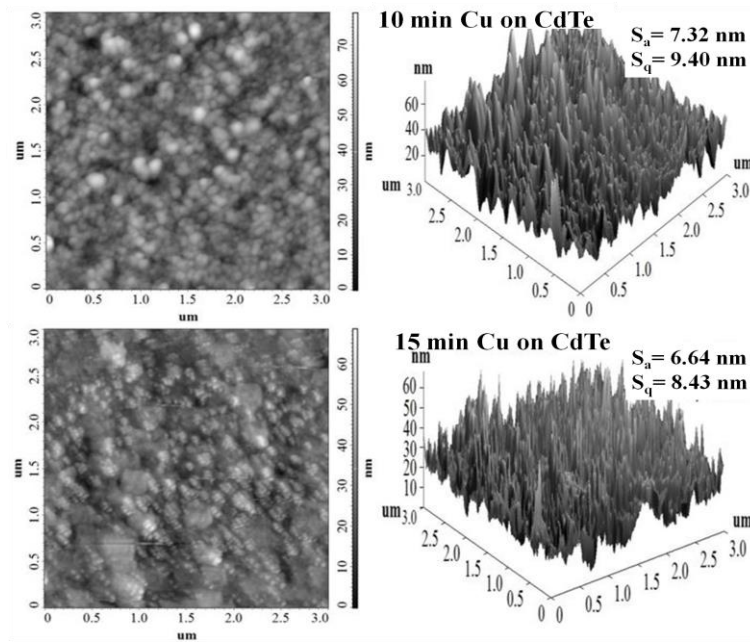


Fig. 2.1. 2D and 3D AFM images for Cu deposited CdTe thin film for deposition times 10 min and 15 min showing the roughness values.

Table 3: Measured values of average roughness ( $S_a$ ) and RMS roughness ( $S_q$ ) of Cu deposited CdTe thin films ( $1.2 \mu\text{m}$ ) for various deposition times

Deposition Time (Cu Thickness)	Average Roughness, $S_a$ (nm)	RMS Roughness, $S_q$ (nm)
2 min Cu (20 nm)	1.84	2.50
5 min Cu (50 nm)	8.56	10.56
10 min Cu (90 nm)	7.32	9.40
15 min Cu (120 nm)	6.64	8.43

Fig. 3 represents the variation of average and RMS roughness with different Cu deposition times. For 2 min Cu deposition time, the average and root mean square (RMS) roughness was about 1.84 nm and 2.50 nm, respectively. When Cu deposition time was increased to 5 min (thickness of 50 nm), the average and root mean square value of the roughness drastically boosted to 8.56 nm and 10.56 nm, respectively. The roughness values decrease slightly for further increase in Cu deposition time. Surface roughness was strongly affected by Cu layer thickness. For lower concentration of Cu, the roughness values were lower. The roughness values enlarged until 5 min Cu growth time and then reduced slightly. Cu thickness was higher when Cu was deposited for 15 min but lower values of roughness were observed again. Therefore, trade-off between different Cu deposition times and Cu thickness is requisite for better device stability.

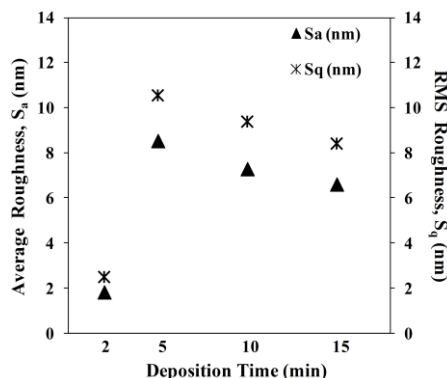


Fig 3. Variation of average and RMS roughness with different Cu deposition times

### 3.3 Optical Properties Analysis by UV-Vis Spectrometry

The main intention of using UV-Vis spectrometry is to examine the optical properties such as transmission, absorption and optical band gap of the films. The absorption and transmission spectra recorded by using Lambda 900 UV/Vis/NIR spectrometer were obtained from the Cu deposited CdTe thin films. The transmission spectra for the various Cu deposition times are shown in Fig. 4 which was recorded for wavelengths ranging from 400 nm to 900 nm. The films are very pertinent as a good quality absorber layer for photovoltaic applications because all the grown films display a transmittance below 10% along the visible range.

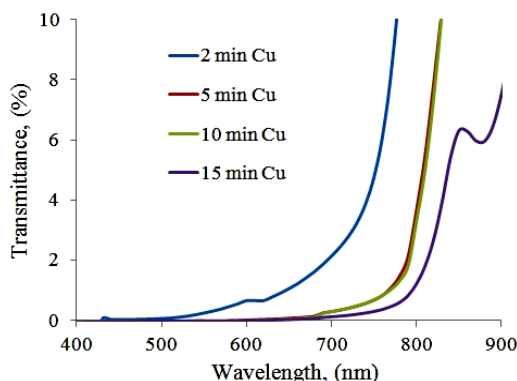


Fig 4. Transmittance versus wavelength spectra for Cu deposited CdTe thin film for deposition times 2 min, 5 min, 10 min and 15 min

The optical absorbance data was employed to calculate the band gap. By extrapolating the straight line portion of the graph to zero absorption coefficients, the band gap energy was achieved. The intercept on the energy axis determines the value of energy band gap [26]. The band gap of Cu deposited CdTe thin films were calculated from the following equation [27, 28].

$$\alpha = A (h\nu - E_g)^{1/2} / h\nu \quad (6)$$

Where, ' $\alpha$ ' is the absorption co-efficient; ' $A$ ' is constant; ' $h\nu$ ' is photon energy and ' $E_g$ ' is the band gap. The graphs of  $(\alpha h\nu)^2$  vs  $h\nu$  are plotted in Fig. 5 enabling the energy band gaps of the films to be determined. The band gap was found to be 1.50 eV for a 2 min Cu growth. Slightly lower band gap values were observed for higher Cu concentrations. Table 4 shows the band gap values of Cu deposited CdTe thin films for different Cu deposition times.

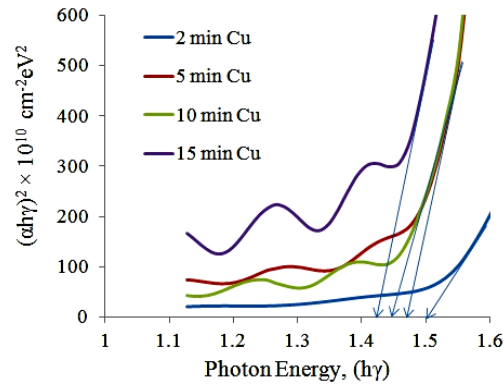


Fig 5. Plot of  $(ah\nu)^2$  versus photon energy  $h\nu$  of Cu deposited CdTe thin film for deposition times 2 min, 5 min, 10 min and 15 min.

Table 4: Band gap values of Cu deposited CdTe films ( $1.2 \mu\text{m}$ ) for different Cu deposition times

Deposition Time (Cu Thickness)	Band gap (eV)
2 min Cu (20 nm)	1.50
5 min Cu (50 nm)	1.44
10 min Cu (90 nm)	1.46
15 min Cu (120 nm)	1.42

### 3.4. Electrical Properties Analysis by Hall Effect Measurement

The electrical properties of the Cu deposited CdTe thin films prepared at various Cu deposition times were inspected by Hall-Effect measurements with an integrated resistivity/Hall measurement system (ECOPIA 3000). The measurements were carried out at room temperature. The magnitude of the magnetic field and the current source was 0.55 T at the maximum and 40 nA, respectively. From this study, the carrier concentration, mobility, resistivity and Hall coefficients were deduced for various Cu deposition times. The measured carrier concentration, mobility, resistivity and Hall coefficients are presented in Table 5. The variation of carrier concentration and resistivity with the variation of Cu deposition times are shown in Fig. 6.

Table 5: Electrical parameters of Cu deposited CdTe thin films ( $1.2 \mu\text{m}$ ) for various Cu concentrations

Deposition Time (Cu Thickness)	Carrier Concentration [ $\times 10^{18}$ ] ( $\text{cm}^{-3}$ )	Mobility ( $\text{cm}^2/\text{Vs}$ )	Resistivity [ $\times 10^4$ ] ( $\Omega\text{-cm}$ )	Hall Co-efficient ( $\text{cm}^3/\text{c}$ )
2 min Cu (20 nm)	5.3	92.8	2.2	18
5 min Cu (50 nm)	6.8	417	4.4	32
10 min Cu (90 nm)	7.5	957.4	6.6	25
15 min Cu (120 nm)	6.2	1391	1.8	61



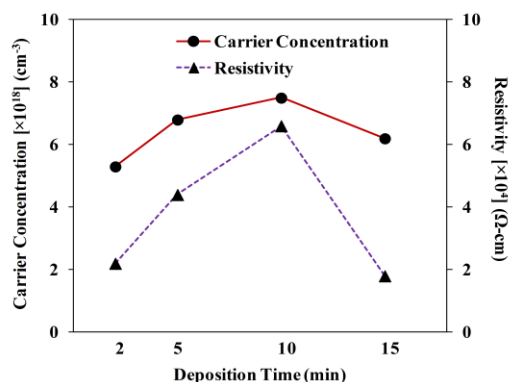


Fig 6. Variation of bulk concentration and resistivity with the variation of Cu deposition times

The highest mobility ( $1391 \text{ cm}^2/\text{Vs}$ ) was obtained for 15 min Cu deposition time but having the lowest resistivity. This observation can be correlated to the higher carrier concentration. Carrier-carrier scattering effect is much apparent for films with higher carrier concentration due to the increased chance of carrier collisions, which in return directs to lower mobility. The value of mobility enhanced with the increment of Cu deposition times. It was also perceptible that, carrier concentration of the films was in the order of  $10^{18} \text{ cm}^{-3}$ , was maximum ( $7.5 \times 10^{18}/\text{cm}^3$ ) for 10 min Cu growth (or 90 nm thick Cu layer) on CdTe. For 2 min Cu deposition time, the Hall coefficient value was the lowest ( $18 \text{ cm}^3/\text{c}$ ). All electrical parameters depicted moderate values for 5 min Cu deposition time (50 nm Cu) on CdTe. From this analysis it can be concluded that, variation of Cu deposition times as a function of Cu concentration has an immense impact on the electrical properties of the film. With the increment of Cu deposition times, crystallinity was increased as evident from the XRD peak. Narrow line broadening of the peak designates higher FWHM and afterwards highest crystallite size. From the literature, it was found that better crystallinity results in lower electrical resistivity which might be owing to reduced carrier scattering and recombination across the grain boundaries.

### 3.5 Surface Morphology Analysis by FESEM

Field emission scanning electron microscopy (FESEM) is a technique to find out the growth mechanism, surface morphology, microstructure, grain size and shape of the films. To evade shunting and achieve a cell with higher efficiency, the film must be continuous, free of voids and also should have large particles. The film's microstructure must have negligible density of crystalline defects. FESEM images were taken for CdTe layer to explore the surface morphology. Fig. 7 shows FESEM images of Cu deposited CdTe thin films for various Cu deposition times.

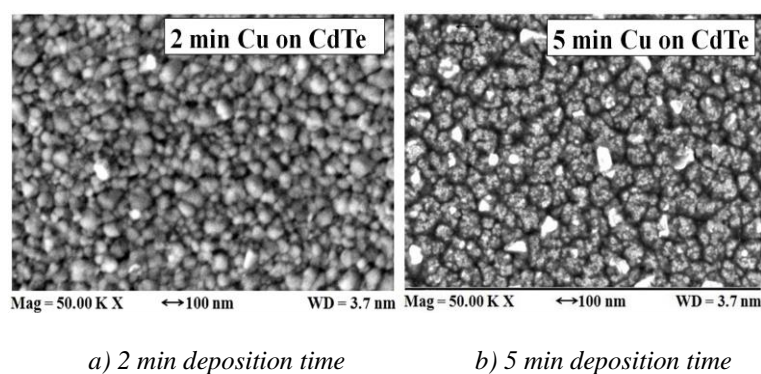


Fig 7.1: FESEM images of Cu deposited CdTe thin films for various Cu concentrations

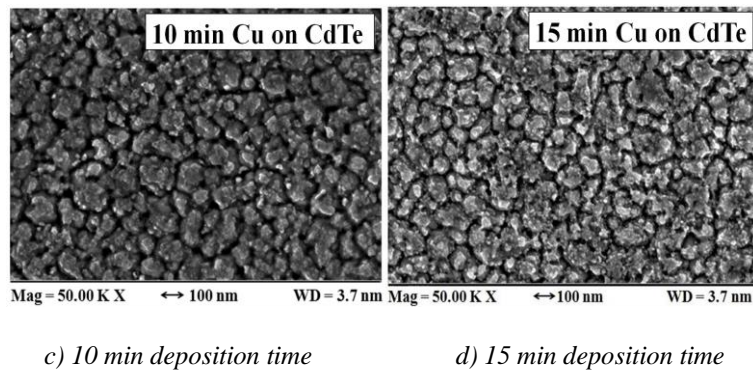


Fig 7.2: FESEM images of Cu deposited CdTe thin films for various Cu concentrations

From the micrographs, it is evidently detected that the films were scattered throughout all the regions and the films have pinholes. Pinholes typically emerge when the CdTe layer is not thick enough. There is fundamental necessitate to optimize CdTe deposition process to get the larger grain. The images illustrate that the surface morphology and the average grain size of the films is greatly reliant on the Cu deposition times as a function of Cu concentration. The grains were appointed in the thin films with a compact and uneven surface. The deposited films were found without any void or cracks, and they cover the substrates very well. The grain sizes were almost constant for all the Cu deposition times. The average grain size of the films was found to be in the range of 100–150 nm. The different morphology and structure (crystalline) of the films might be owing to the defects constructed by different Cu thicknesses. This is because the rate of particle aggregation during the film preparation which is a key factor that directs the morphology and structure (crystalline) of the films.

### 3.6 EDX Analysis

Energy-dispersive X-ray (EDX) spectroscopy is utilized for the elemental analysis or chemical characterization of sample. Basically, this technique is based on the study of a sample through interactions between electromagnetic radiation and matter. EDX analysis can generate data, which consist of spectra depicting peaks equivalent to the elements creating up the true composition of the sample being analyzed. EDX analysis is also competent of doing elemental mapping and image analysis of a sample.

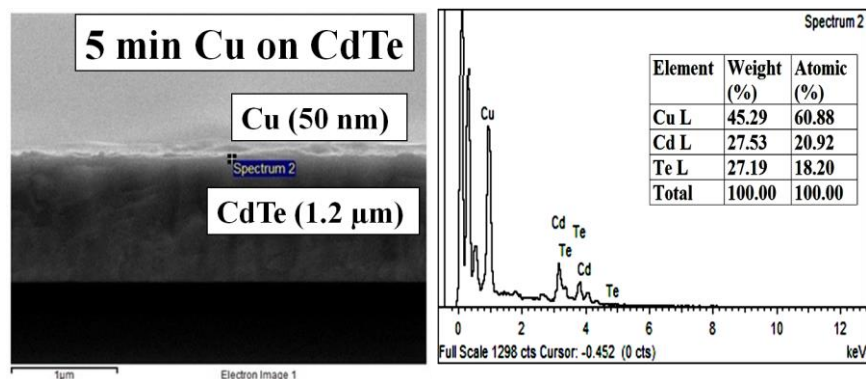


Fig 8.1 EDX results of Cu deposited CdTe thin films for 5 minutes Cu deposition times

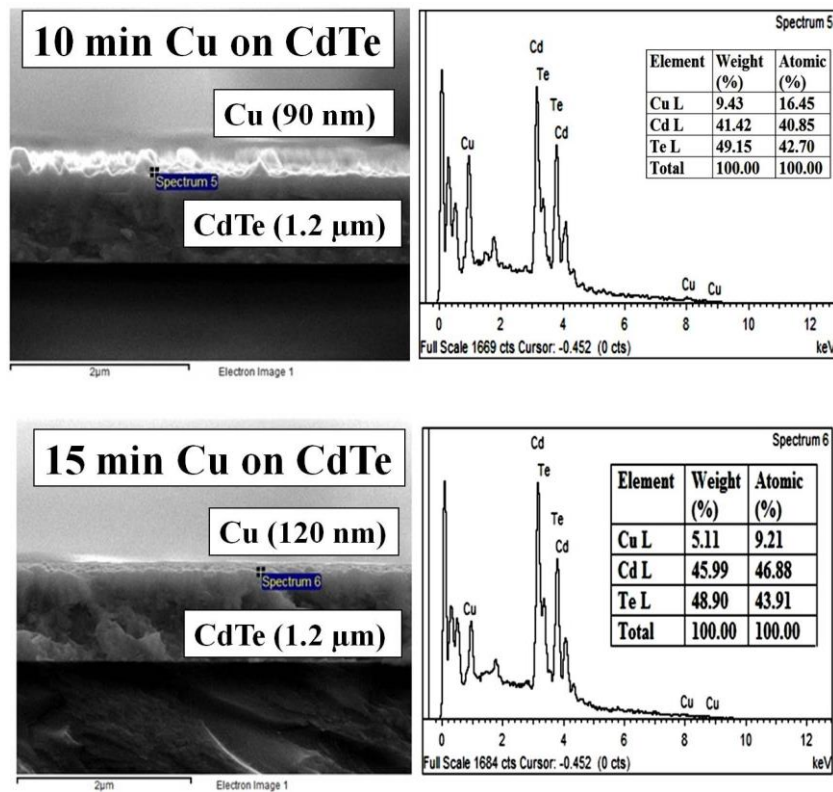


Fig 8.2 EDX results of Cu deposited CdTe thin films for 10 and 15 minutes Cu deposition times

The compositions of the thin films were confirmed by energy dispersive X-ray analysis (EDX). Fig. 8 shows a representative EDX spectrum of the thin films for various Cu deposition times showing the compositional ratio. The percentages of Cu, Cd and Te are shown in Table 6. It is noticeable that the films prepared with low Cu deposition time exhibits the maximum amount of Cu compositional ratio. For increased Cu deposition time, Cu is diffused through CdTe and consequently the compositional ratio of Cu reduced. On the other hand, the compositional ratio of Cd and Te exhibits rising value with increased Cu concentration.

Table 6: EDX Data of Cu deposited CdTe thin films for various Cu deposition times

Deposition Time (Cu Thickness)	Element	Weight (%)	Atomic (%)
5 min Cu (50 nm)	Cu	45.29	60.88
	Cd	27.53	20.92
	Te	27.19	18.20
10 min Cu (90 nm)	Cu	9.43	16.45
	Cd	41.42	40.85
	Te	49.15	42.70
15 min Cu (120 nm)	Cu	5.11	9.21
	Cd	45.99	46.88
	Te	48.90	43.91

#### 4. Solar Cell Fabrication

From the light I-V (LIV) measurement, performance parameters of the fabricated CdTe solar cells for various Cu deposition times were acquired. The fabricated cells have an active area of

0.25 cm<sup>2</sup> (0.5 cm x 0.5 cm). Fig. 9 illustrates the J-V curve for complete CdTe solar cells for the structure (ITO/CdS/CdTe/Cu<sub>2</sub>Te/Ag). Table 7 represents the performance parameters for CdTe solar cells for different Cu concentrations.

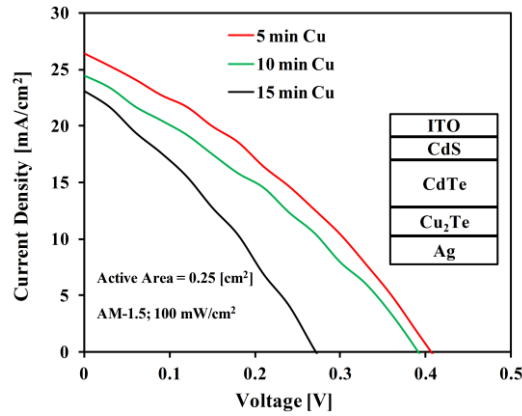


Fig 9. Measured J-V characteristic curves for different Cu deposition times

Table 7: Measured CdTe solar cell parameters for different Cu concentrations

Deposition Time (Cu Thickness)	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	Fill Factor (FF)	Efficiency (%)
5 min Cu (50 nm)	0.42	26.4	0.34	<b>3.77</b>
10 min Cu (90 nm)	0.46	24.4	0.32	<b>3.60</b>
15 min Cu (120 nm)	0.28	23.2	0.30	<b>1.95</b>

From Table 7, it is observed that the highest conversion efficiency of 3.77% ( $V_{oc} = 0.42$  V,  $J_{sc} = 26.4$  mA/cm<sup>2</sup> and Fill Factor = 0.34) is attained for CdS/CdTe solar cell when the Cu deposition time is 5 min (50 nm thick Cu layer). With the increase of Cu deposition times, the efficiency shows decreasing trend. Efficiency of 3.60% has been achieved for 10 min Cu growth (90 nm) on CdTe while the efficiency is the lowest for 15 min Cu deposition (120 nm) on CdTe. The lower conversion efficiency for higher Cu deposition time on CdTe might be due to the loss of  $J_{sc}$ ,  $V_{oc}$  along with FF components and the lower photocurrent generation. The photocurrent loss might be owing to the electron-hole-pair (EHP) recombination. Severe recombination of EHPs will also deteriorate the  $V_{oc}$ . It can be said that recombination mechanism is dominant in the cell due to shunting for higher (15 min) Cu deposition time. When Cu is deposited for 15 min on CdTe, copper concentration increased, diffused through CdTe and degraded the cell performance. This study illustrates Cu as an effective dopant for CdTe at an optimum concentration range to form Cu<sub>2</sub>Te layer. Reaching optimum Cu concentration for CdTe stabilizes the cell performance. Exceeding the optimum Cu concentration caused a reversal impact to the efficiency and  $V_{oc}$  which could be attributed to self-compensation in the CdTe bulk [29]. Effective acceptors created from Cu filled in Vcd were compensated by the excess Cu which formed Cu-interstitial defects in the CdTe thin film. Cu-interstitial is a donor state hence lowering the overall effective holes' density [29]. Undoped CdTe has poor performance owing to inadequate acceptor from CdTe own states that caused too low effective holes density. However, all in all, it can be said that thorough optimization of process such as post-deposition annealing as well as subsequent layer deposition are necessary to achieve higher conversion efficiency of this kind of device configuration.

## 5. Conclusions

In this study, the impact of Cu concentration on the CdTe thin film properties and solar cells performance has been explored. An optimum range of Cu concentration is found that could lead to higher  $V_{oc}$  as well as efficiency. Exceeding optimum range of Cu doping caused a drop in  $V_{oc}$  and efficiency due to strong self-compensation. By analyzing structural, topological, optical, electrical, morphological properties and solar cells performance, it can be concluded that Cu deposition time and subsequent annealing should be optimized to achieve higher cell performance if thinner Cu layer or small quantity has to be diffused to have proper contact.

If the Cu layer is thin enough to begin with, its influence on the back barrier height is less noticeable and thus allows for better performance of the cells without any back contact heat activation treatment. This study implies that ultra thin (around 1  $\mu\text{m}$ ) CdTe cells require shortened Cu activation time of about 5 to 10 minutes. An optimum temperature for annealing is also necessary to activate the Cu and to enable diffusion of Cu to form  $\text{Cu}_2\text{Te}$  layer near the back contact. Therefore, choosing the right Cu deposition time would be important to yield precise Cu concentration that would be suitable for CdTe thin film solar cell fabrication.

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