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Research Article

The Role of Dopant Concentration on Conductivity and Mobility of CdTe Thin Films

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Films of CdTe pure and doped with various atomic percentages of Al and Sb (0.5, 1.5 & 2.5) were prepared, and their electrical properties were investigated. The films were prepared by thermal evaporation on glass substrates at two substrate temperatures (T_s = RT & 423 K). The results showed that the conduction phenomena of all the investigated CdTe thin films on glass substrates are caused by two distinct mechanisms. Room temperature DC conductivity increases by a factor of four for undoped CdTe thin films as T_s increases and by 1-2 orders of magnitude with increasing dopant percentage of Al and Sb. In general, films doped with Sb are more efficient than Al-doped films. The activation energy (E_{a2}) decreases with increasing T_s and dopant percentage for both Al and Sb. Undoped CdTe films deposited at RT are p-type convert to n-type with increasing T_s and upon doping with Al at more than 0.5%. The carrier concentration decreases as T_s increases while it increases with increasing dopant percentage. Hall mobility decreases more than three times as Al increases whereas it increases about one order of magnitude with increasing Sb percentage in CdTe thin films deposited at 423 K and RT, respectively.

1. Introduction

Cadmium telluride (CdTe) is a member of the II–VI family of compound semiconductors that shows unique properties making it important and quite suitable for several applications, such as utilization in ternary alloys (CdHgTe), and use as a buffer layer for the growth of $Hg_{1-x}Cd_xTe$ (MCT) or $Hg_{1-x}(Cd_yZn_{1-y})_xTe$ (MCZT) for infrared detectors [1, 2]. Its band gap of 1.5 eV, just in the middle of the solar spectrum, and it processes high absorption coefficient (α) ($>10^4\,cm^{-1}$) for the visible solar spectrum [3]. A 2 μm thick layer of CdTe is completely opaque, while a 20 μm thick layer of Si is required to absorb a similar radiation intensity [4]. These properties make CdTe a good candidate material for photovoltaic conversion, and accordingly several companies now commercialize CdTe-based solar cells [5]. CdTe is unique among the II–VI series of semiconducting compounds, as it exhibits both n-type and p-type conductivity, making diode technology and field effect transistors possible, and it permits the fabrication of solar cells in both homojunction and heterojunction configuration [6]. Its high average atomic number of 50, wide band gap, high resistivity, and good transport properties make it very suitable for X-ray and gamma-ray detectors [7, 8].

The purpose of the present work is to study the effect of the substrate temperatures and dopant percentages of Al and Sb on the electrical properties of CdTe thin films. The electrical properties, including the DC conductivity and Hall Effect, were studied in dark for undoped and doped CdTe thin films with various concentrations of Al and Sb (0.5, 1.5 & 2.5)% deposited onto glass substrates at substrate temperatures of RT and 423 K. The transport mechanisms in these films were determined from the measurement of the dark DC conductivity and the type, concentration, and the mobility of the carriers have been estimated from Hall Effect measurement.

2. Experimental Procedure

The films of CdTe are deposited by thermal evaporation around 10^{-6} Torr vacuum pressure. Different deposition

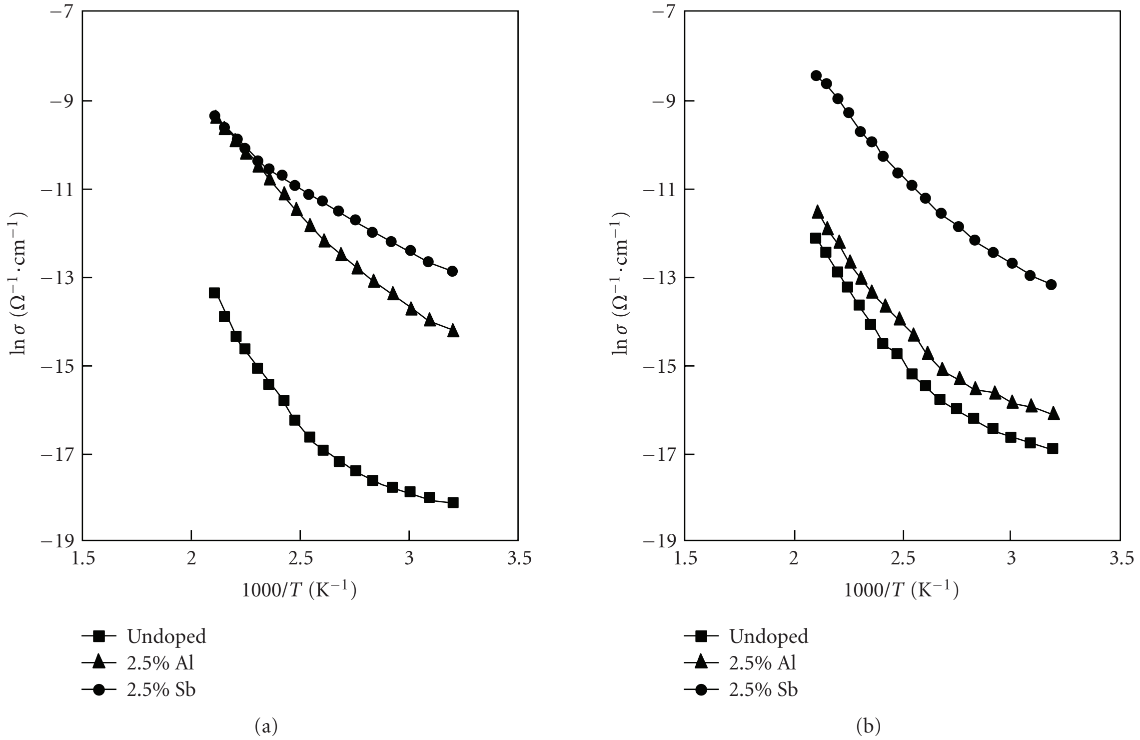

Figure 1: (a) T_S= RT. (b) T_S = 423 K.

conditions were introduced to prepare the films such as substrate temperatures (T_s = RT & 423 K) and dopant percentages of Al for n-type and Sb for p-type thin film. The film thickness of about 0.5 μm was grown on corning glass 7059. The composition of the prepared films was determined using energy dispersive X-ray analysis (EDX) on a Jeol JSM5600 SEM, and the EDX scan results coincide with the theoretical percentage values of Cd, Te, Al, and Sb in undoped and doped CdTe thin films.

The electrical properties of pure and doped CdTe thin films with different percentages of Al and Sb were measured. The dark DC conductivity (σ) for prepared films was measured as a function of substrate temperature and dopant percentages of Al and Sb. Digital electrometer type Keithely 616 was used for current and voltage measurements. Hall Effect was used to find the type of film, the carrier concentration of dopant (Al & Sb), and mobility of carriers. For more details see [9].

3. Results and Discussion

3.1. DC Conductivity of CdTe Thin Films. Figures 1(a) and 1(b) show the variation of the dark DC electrical conductivity (σ) with temperature (T) in the form of $\ln\sigma$ versus 1000/T plots for undoped and 2.5% Al and 2.5% Sb-doped CdTe thin films deposited at RT and 423 K. The conductivity of all the investigated thin films increased with increasing temperature in the range (303–473) K. This indicates that undoped and doped CdTe films with various concentrations of both type of dopant deposited at RT and 423 K have a semiconductor like behavior. On the other hand, the plots of $\ln\sigma$ versus $1000/T$ are nonlinear showing two clear different regions one at relatively high-temperature (383–473) K and the other relatively at low-temperature (303–373) K. This behavior revealed that the conduction phenomena of the investigated thin films proceed through two distinct conduction mechanisms. The plots are further analyzed to calculate the activation energies E_{a1} and E_{a2} from the slopes of the curves in both regions using equation [10]:

$$\sigma = \sigma_o \exp\left\{-\frac{E_a}{k_B} T\right\}, \quad (1)$$

where σ_o is the pre exponential factor or temperature independent conductivity, k_B is Boltzmann constant, and T is temperature.

The data shows in Figure 1, at higher temperature, the conductivity is strongly dependent on the temperature. Hence, the conduction mechanism of E_{a2} in this case is due to carriers excited beyond the mobility edges into extended states. At relatively lower temperatures, the conduction is due to carriers excited into localized states at the band edges [10].

The DC conductivity at RT (σ_{RT}), E_{a1}, and E_{a2} values for undoped and doped CdTe thin films with various concentration of Al and Sb (0.5, 1.5 & 2.5)% deposited at RT and 423 K are tabulated in Table 1. It is observed that as the T_s increased, σ_{RT} of undoped CdTe thin film varied from $1.3 \times 10^{-8}\ \Omega^{-1}\cdot\text{cm}^{-1}$ to $5.1 \times 10^{-8}\ \Omega^{-1}\cdot\text{cm}^{-1}$, that is, decrease by around a factor of four. Similar behavior was reported in literature for CdTe thin films deposited using thermal evaporation [11, 12] and close-spaced sublimation

Table 1: Values of ρ_{RT}, σ_{RT}, E_{a1} and E_{a2} for undoped and doped CdTe thin films deposited at RT and 423 K.

CdTe thin film	T_s (K)	$\rho_{RT} \times 10^7$ ($\Omega\cdot$cm)	$\sigma_{RT} \times 10^{-6}$ ($\Omega^{-1}\cdot$cm^{-1})	E_{a1} (eV)	Temp. range (K)	E_{a2} (eV)	Temp. range (K)
Undoped	RT	7.692	0.013	0.146	303–363	0.612	363–473
	423	1.961	0.051	0.189	303–363	0.594	363–473
Doped with							
0.5% Al	RT	8.333	0.012	0.255	303–363	0.599	363–473
	423	1.449	0.069	0.174	303–353	0.566	353–473
1.5% Al	RT	1.075	0.093	0.189	303–363	0.568	363–473
	423	1.190	0.084	0.105	303–343	0.562	343–473
2.5% Al	RT	0.150	0.668	0.272	303–353	0.475	353–473
	423	1.064	0.094	0.154	303–353	0.532	353–473
0.5% Sb	RT	0.725	0.138	0.288	303–363	0.574	363–473
	423	1.961	0.051	0.209	303–363	0.573	363–473
1.5% Sb	RT	0.142	0.704	0.246	303–363	0.519	363–473
	423	0.252	0.397	0.175	303–343	0.538	343–473
2.5% Sb	RT	0.040	2.506	0.242	303–403	0.414	403–473
	423	0.056	1.796	0.271	303–363	0.505	363–473

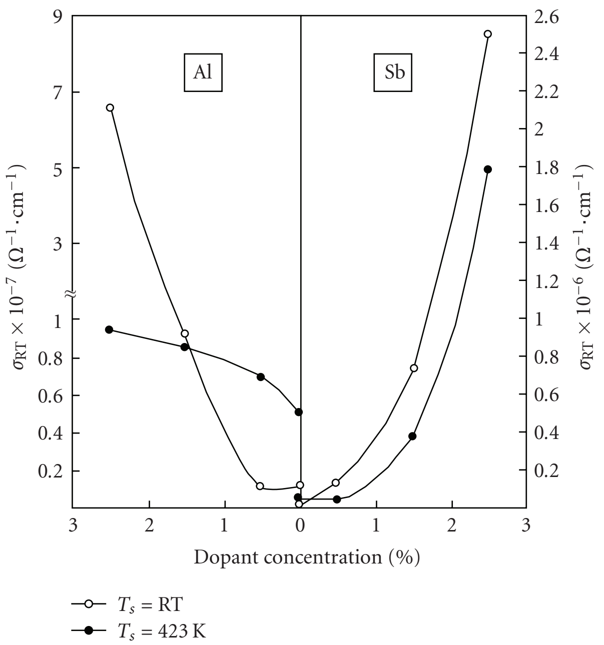

Figure 2

(CSS) techniques [13]. Lee et al. [12] suggested that the difference in conductivity found in CdTe films grown at different temperatures can be explained by the reduction of the number of grain boundaries due to the increase of the grain size. They found that the dark resistivity of CdTe films with thickness in the 2-3 μm range is reduced from $6 \times 10^7\ \Omega\cdot$cm at RT to $5.4 \times 10^6\ \Omega\cdot$cm at 573 K. Our results showed that the dark resistivity at RT for undoped CdTe is on order of $10^7\ \Omega\cdot$cm. Similar outcomes were obtained by Niraula et al. [14] for undoped CdTe films grown by MOCVD with a thickness of 0.5 μm at T_s in the 423–573 K range. Also the same results were obtained by Rusu et al. [15] and Nory [16] for thermally evaporated CdTe thin films at RT with a thickness in the range of 0.3–0.5 μm and of 0.5 μm, respectively. However, other researches [17–20] reported lower values than our results. This discrepancy is possibly due to the difference in the preparation techniques and in film deposition conditions.

Figure 2 shows the variation of σ_{RT} with dopant concentration of Al and Sb for CdTe thin films deposited at RT and 423 K. It can be observed from this figure and Table 1 that, in general, σ_{RT} of CdTe films increased when such films were doped with Al or Sb depending on the dopant concentration. Similar behaviors were reported by Mohammed [19] for CdTe doped with Zn and Shehab [21] for CdTe doped with P.

The data tabulated in Table 1 shows that increasing the doping concentration from 0.5% to 2.5% Al in CdTe films deposited at RT has caused an increase in σ_{RT} from $1.2 \times 10^{-8}\ \Omega^{-1}\cdot$cm^{-1} to $6.68\times10^{-7}\ \Omega^{-1}\cdot$cm^{-1} and a slight increase from $6.9 \times 10^{-8}\ \Omega^{-1}\cdot$cm^{-1} to $9.4 \times 10^{-8}\ \Omega^{-1}\cdot$cm^{-1} for films deposited at 423 K. On the other hand, the σ_{RT} increases from $1.38 \times 10^{-7}\ \Omega^{-1}\cdot$cm^{-1} to $2.506 \times 10^{-6}\ \Omega^{-1}\cdot$cm^{-1} for films grown at RT and from $5.1 \times 10^{-8}\ \Omega^{-1}\cdot$cm^{-1} to $1.796 \times 10^{-6}\ \Omega^{-1}\cdot$cm^{-1} for film prepared at 423 K as the doping concentration of Sb increased from 0.5% to 2.5% in the films. These results indicated that the doping of CdTe with 2.5% Al and Sb leads to increase in σ_{RT} by 1-2 orders of magnitude, and this is in agreement with Bayhan and Erçelebi [22]. They showed that all evaporated, undoped CdTe films deposited at 473 K have high resistivity ($\geq 10^{10}\ \Omega\cdot$cm). This value was reduced by 1-2 orders of magnitude for CdTe films doped with Sb. In general the data shown in Table 1 indicate, that Sb is more efficient than Al since Sb doping exhibits a higher σ_{RT} than that for Al doping.

Table 1 also illustrates the dependence of the activation energies E_{a1} and E_{a2} on the doping percentage of Al and Sb for CdTe thin films deposited at RT and 423 K. From this figure and Table 1, the activation energy E_{a2} for undoped CdTe film is found to vary from 0.612 eV to 0.594 eV as T_s

Table 2: Values of carrier concentration and μ_H for undoped and doped CdTe thin films deposited at RT and 423 K.

CdTe thin films	T_s (K)	Carrier concentration $\times 10^{13}$ (cm^{-3})	$\mu_H \times 10^{-2}$ ($cm^2/V\cdot s$)	Type
Undoped	RT	1.107	0.756	P
	423	0.483	6.599	N
Doped with				
0.5% Al	RT	0.172	4.360	P
	423	0.856	5.052	N
1.5% Al	RT	2.628	2.214	N
	423	1.151	4.561	N
2.5% Al	RT	6.961	5.997	N
	423	3.142	1.869	N
0.5% Sb	RT	3.836	2.248	P
	423	0.397	8.028	P
1.5% Sb	RT	6.101	7.211	P
	423	5.073	4.891	P
2.5% Sb	RT	13.292	11.783	P
	423	12.566	8.932	P

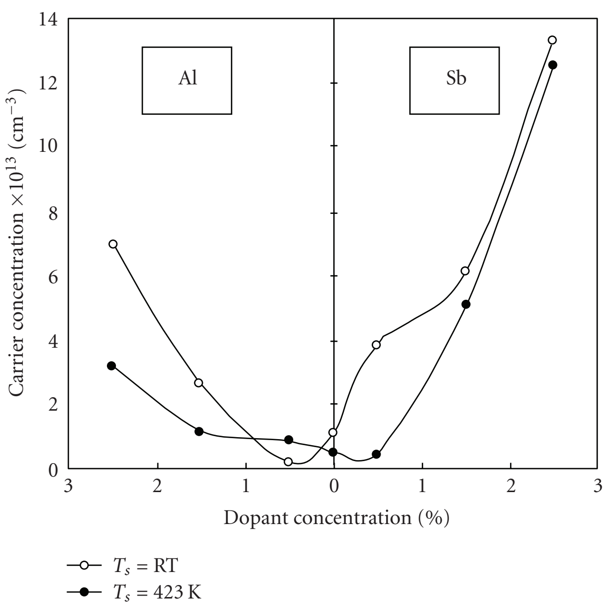

Figure 3

increased. This is in agreement with Al-Shadidi [23] whereas it is in contrast with Rasheed [24], who showed an increase in the activation energies with increasing substrate temperature from 300 K to 423 K. A noticeable change is observed in the activation energy E_{a2} upon doping with Al and Sb. The data shown in Table 1 indicate a decrease of E_{a2} from 0.599 eV to 0.475 eV at RT and from 0.566 eV to 0.532 eV at 423 K with increasing Al doping concentration from 0.5% to 2.5%. The data also revealed that E_{a2} decreases from 0.574 eV to 0.414 eV at RT and from 0.573 eV to 0.505 eV at 423 K as the concentration of Sb increases from 0.5% to 2.5% in these films. The decrease in the activation energy with increasing of dopant concentration was also observed by other researchers [19, 25, 26].

The above mentioned behavior of E_{a2} with doping concentration might be due to a decrease in the defects such as dangling bonds and vacancies as well as the creation of impurity levels within the bandgap [25]. The behavior of the activation energy E_{a1} with dopant concentrations of Al and Sb in CdTe thin films is not monotonic, since its value decreases then increases with increasing dopant concentration from 0.5% to 2.5% as shown in Table 1.

3.2. Carrier Concentration and Hall Mobility. The Hall effect measurements have been used to investigate the type and concentration of charge carriers and Hall mobility (μ_H) for undoped, Al- and Sb-doped CdTe thin films deposited at RT and 423 K, and the results are presented in Table 2. As can be seen, holes were predominant in the conduction process for undoped CdTe films deposited at RT (p-type) while electrons were predominant for undoped CdTe films deposited at 423 K (n-type). These results are in agreement with other researchers [24, 27]. All of the CdTe thin films doped with Sb which were deposited at RT and 423 K were found to be p-type, whereas those doped with Al and deposited at RT and 423 K were found to be n-type except for films doped with 0.5% Al at RT as shown in Table 2.

Figure 3 shows the variation of carrier concentrations with different dopant concentration of Al and Sb for CdTe thin films deposited at RT and 423 K. As shown in this figure and Table 2, the carrier concentration for undoped CdTe films at RT is higher than that at 423 K. This is due to type conversion of p-type films into n-type as T_s increased. Upon doping CdTe films with 0.5% Al at RT, the carrier concentration decreases and then increases with further increasing in Al doping to 2.5% due to the conversion of the films into n-type. For the corresponding films deposited at 423 K, an increase in carrier concentration with increasing doping (Al) from 0.0 to 2.5% is observed. The carrier concentration increases with increasing Sb dopant from 0.0 to 2.5% at RT while it decreases upon doping CdTe films with

0.5% Sb and then increases with further increasing to 2.5% Sb at 423 K.

The variation of the Hall mobility (μ_H) with dopant percentage of Al and Sb for CdTe thin films deposited at RT and 423 K is also shown in Table 2. One can notice from this table that μ_H varied in the range (0.756–5.997) $\times 10^{-2}$ cm^2/V·s at RT, and its value decreases more than three times from 6.599×10^{-2} cm^2/V·s to 1.869×10^{-2} cm^2/V·s at 423 K, as the doping concentration of Al increased from 0.0 to 2.5%, while μ_H increases from 0.756×10^{-2} cm^2/V·s to 11.783×10^{-2} cm^2/V·s at RT, which is more than one order of magnitude, as the doping concentration of Sb increase from 0.0 to 2.5%. The value of μ_H varies between 6.599×10^{-2} cm^2/V·s and 8.932×10^{-2} cm^2/V·s at 423 K with increasing Sb doping from 0.0 to 2.5%.

Our results of the increase in μ_H with dopant percentage of Sb in CdTe thin films at RT is similar to that found by Huber and Lopez-Otero [27]. They noticed that for CdTe films doped with In a tendency for the mobility to decrease with decreasing carrier concentration. Also this behavior is in agreement with Al-Fwadi et al. [28] for CdSe doped with Cu. They found that μ_{H} increases exponentially with increasing Cu concentration which was attributed to the reduction of the scattering of the carrier from the surface as well as due to the elimination of the defects in the films and increase in crystallinity which consequently decreases the number of grain boundaries.

4. Conclusions

Electrical studies of CdTe thin films deposited on glass substrates using thermal evaporation and doped with various concentrations of Al and Sb indicate that:

(i) undoped CdTe thin films deposited at RT are p-type that convert to n-type as T_s increased and with Al doping of more than 0.5%,

(ii) increasing dopant percentage for both Al and Sb result in an increase in the DC conductivity by 1-2 order of magnitudes and in the carrier concentration,

(iii) increasing dopant percentage for both Al and Sb results in a decrease in the activation energy,

(iv) hall mobility decreases by more than three times as Al increases whereas it increases about one order of magnitude with increasing Sb in CdTe film deposited at 423 K and RT, respectively.

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