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Trap depth analysis of thermally deposited CdSe thin films

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Photocurrent decay characteristics were studied in CdSe thin films deposited by technique of thermal evaporation on suitably cleaned glass substrate held at elevated substrate temperatures. Two different decay times were found which correspond to two distinct trap levels. The trap depths were evaluated under different conditions of temperature and intensity. The trap depths were found to increase with ambient temperature and intensity of white light illumination. The estimated trap depths range from 0.4 eV to 0.7 eV.

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1. Introduction

CdSe is a binary semiconductor and among the II-VI group of semiconductor compounds, it is considered as an important material for the development of different optoelectronic devices [1,2,3] because of its high photosensitive nature and suitable intrinsic band gap [4]. In recent years special attention has been given to the investigation of optoelectronic properties of CdSe thin films in order to improve the performances of devices and also for finding new applications [5,6]. Different growing methods for preparation of CdSe thin films have been reported [7,8]. Physical vapour deposition method is often used because it offers many possibilities to modify the deposition parameters and to obtain films with determined structure and properties. Irrespective of preparation conditions such deposited films are associated with different type of native and foreign imperfections which greatly influence the optoelectronic properties of the films. Native defects such as various traps having energy in the range 0.15 to 0.8 eV [9,10] can cause a considerable change in the electrical and optical properties of semiconductor thin films. These defects characterize the electronic properties of the materials, because they give rise to charge center acting as donors and acceptors [11]. In view of the relative lack of information concerning trapping spectrum in thermally deposited CdSe thin films, in this paper an analysis has been reported regarding the characteristics of various traps in such films from the study of photocurrent decay under different conditions of illumination levels and ambient temperatures.

2. Experimental

Thin films of CdSe were deposited at elevated substrate temperatures (T_s), on chemically and ultrasonically cleaned glass substrates at a vacuum of the order of 10^{-6} Torr. Pure (99.999%) bulk CdSe samples were used as the source material. Deposited films were annealed in vacuum at high temperature and hereafter stored in dry air. Electrode (aluminium) deposition was done on these films in order to obtain a gap type cell configuration of 10 mm × 7 mm geometry. Thin tantalum boats of proper size and shape were used as the source heater. A suitably designed and assembled multiple beam interferometer was used to measure the thickness (t_t) of the films with an accuracy of ±15Å. An ECIL electrometer amplifier of input impedance of $10^{14}\Omega$ (and higher) was used to measure dark and photocurrents. To apply bias, a series of highly stable dry cells of emf 9 volt each were used. The sample was kept suspended by thin enameled copper wires inside a continuously evacuated glass jacket. The entire experimental set up including the observer was housed inside a suitably fabricated Faraday cage in order to avoid pick-up noises. For white light illumination tungsten halogen projector lamp of 250 watt, operating at maximum voltage 24 volt, was used and the intensities were measured by using a highly sensitive APLAB luxmeter. Electrical heater was used to increase the temperature of the thin film sample from room temperature to any desired level. The measurement of temperature was done with the help of copper constantan thermocouple and a digital micro-voltmeter arrangement.

3. Results and discussion

The photocurrent at any instant of time during growth is given by the equation

$$I_t = I_o\{1-\exp(-t/\tau_r)\} \quad (1)$$

where I_o is the maximum photocurrent and τ_r is the growth time of photocurrent. With passage of time the photocurrent reaches a steady state and when the light is turned off current decreases, because the excess number of carrier decreases as a result off rapid recombination. The decay may be represented by the equation

$$I_t = I_o\{\exp(-t/\tau_d)\} \quad (2)$$

where τ_d is the photocurrent decay time. It may be noted that the experimental CdSe thin films exhibited a rapid growth of photocurrent which was followed by an initial fast decay accompanied by a tail. The fast decay is associated with free electron-hole recombination and the subsequent region is due to release of electrons from traps.

The trap depths were calculated by using the following simple decay law

$$I_t = I_o \exp(-pt) \quad (3)$$

where p is the probability of escape of an electron from the trap per second and is given by [12]

$$p = S \exp(-E / kT) \quad (4)$$

where E is the trap depth for electrons below the bottom of the conduction band or top of the valanced band, k is the Boltzmann constant, T is the ambient temperature in K , I_0 is the photocurrent at the termination of illumination, I_t is the photocurrent at any subsequent time t after the termination of illumination and S is the frequency factor defined in terms of number per second that the quanta from the lattice vibrations (phonons) attempt to eject the electron from the trap, multiplied by the probability of transition of the ejected electron to the conduction band [13].

Using the two relations (3) and (4), the expression for trap depth is given by

$$E = kT [\ \ln S - \ln \{ \ln (I_o/I_t) / t\}] \quad (5)$$

The probability of an electron escaping from a trap of depth E and cross-section for its capture S_t, at a temperature T, is given by [14]

$$p = N_{eff}\, v_{th}\, S_t \exp(-E/kT) \quad (6)$$

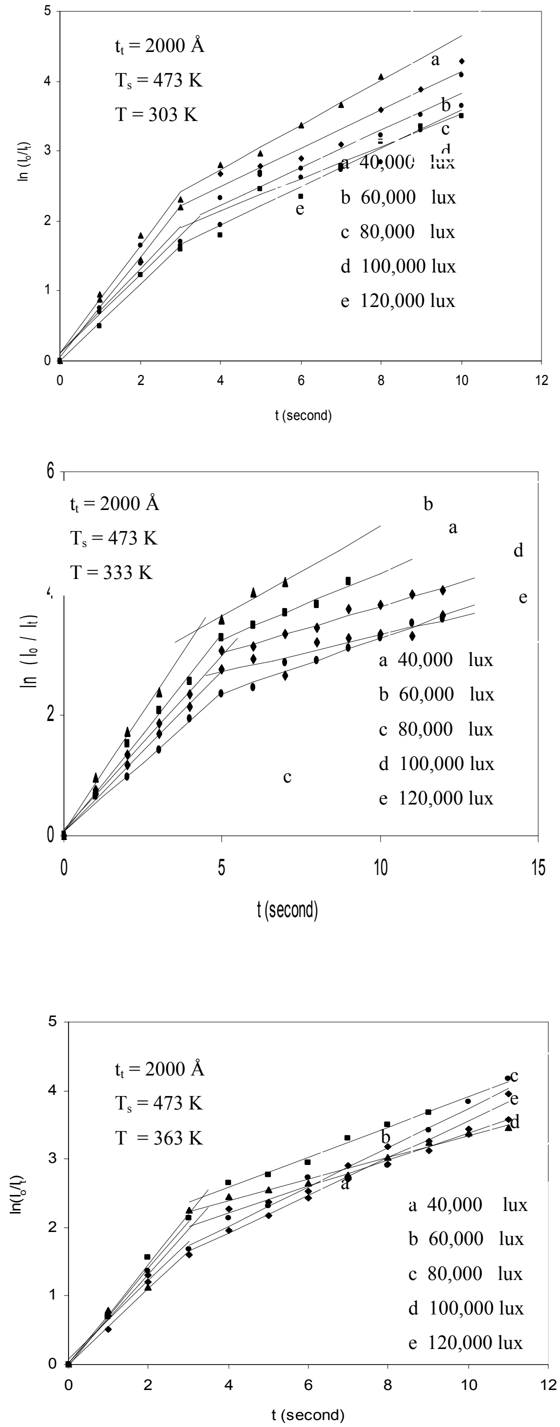

Fig. 1 $\ln(I_0/I_t)$ versus time t plot of a CdSe thin film illuminated by white light of different intensities and at different ambient temperature T.

Table 1 Calculated values of photoconductivity (σ), effective density of states (N_{eff}), frequency factor (S) and trap depth (E) of a CdSe thin film (t_t = 2000Å, T_s = 473K) illuminated by white light of different intensities and at different ambient temperature T.

Ambient temperature (K)	Intensity of illumination (lux)	σ (Ω cm)$^{-1}$ in 10^{-5}	N_{eff} (cm^{-3}) in 10^{10}	S (sec^{-1}) in 10^{6}	E (eV)	
					E_1	E_2
303	40,000	2.28	24.58	14.69	0.43	0.45
	60,000	2.84	30.66	18.33	0.44	0.46
	80,000	3.27	35.30	21.11	0.45	0.47
	100,000	4.19	45.18	27.01	0.45	0.48
	120,000	5.03	54.24	32.43	0.46	0.48
333	40,000	4.19	45.15	28.86	0.51	0.54
	60,000	5.19	55.93	35.76	0.52	0.54
	80,000	6.70	72.26	46.20	0.53	0.55
	100,000	8.38	90.32	57.75	0.55	0.56
	120,000	10.35	111.53	71.31	0.55	0.57
363	40,000	5.94	64.08	42.88	0.63	0.66
	60,000	7.72	83.18	55.67	0.64	0.67
	80,000	10.29	110.80	74.15	0.65	0.68
	100,000	12.48	134.48	90.00	0.66	0.69
	120,000	14.62	157.53	105.4	0.67	0.70

where N_{eff} is the effective density of states in the conduction band and v_{th} is the thermal velocity of the electrons. Here the product $N_{eff}\ v_{th}\ S_t$ represents the frequency factor S.

For finding S, the values of these three parameters N_{eff}, v_{th} and S_t were calculated separately. N_{eff} was calculated from the conductivity data by using the relation, n = σ/eμ [15], where σ is the conductivity evaluated from the experimental data of the photocurrent I_0. In this case, it is assumed that at comparatively low temperatures, the number of occupied energy levels in the conduction band i.e. n is identical with N_{eff}. μ is the mobility of the electrons in CdSe sample whose value was taken as 540 cm^2 V^{-1}sec^{-1}[16]. The thermal velocity v_{th} of an electron was calculated at
different ambient temperatures by using the relation,

$$v_{th} = (2kT / m^*)^{1/2} \tag{7}$$

where m* is the effective mass of an electron which was taken to be 0.13 m_e [17]. The capture cross-section is given by

$$S_t = \pi r^2 \tag{8}$$

where r is the radius of the capture center. It was evaluated by putting Coulomb energy of interaction of an electron with the corresponding trap equal to the thermal energy of the electron at temperature T [18]. i.e.

$$e^2 / r\varepsilon = kT \tag{9}$$

where ε is the dielectric constant of CdSe sample whose value is taken to be 5.76 [19]. Using (9) in (8) the relation for capture cross section is given by

$$S_t = \pi e^4 / k^2T^2\varepsilon^2 \tag{10}$$

At 300 K, $S_t \approx 10^{-10}/\varepsilon^2$ cm^2

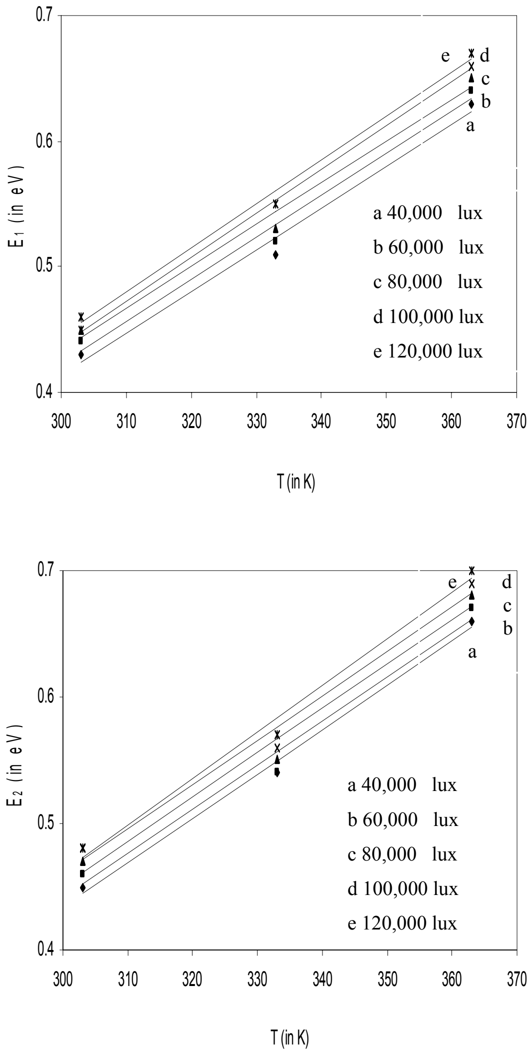

Fig. 2. Trap depths versus ambient temperature (T) under different intensity of illuminations of a CdSe thin film grown at elevated T_s = 473 K.

Using the relation

$$S = N_{eff}\, v_{th}\, S_t \tag{11}$$

the frequency factor, S, at different ambient conditions were evaluated. The different calculated values of N_{eff} and S are shown in Table 1. From the data of the table, it is seen that there is a gradual increase in the value of S with ambient temperature as well as with intensity of white light illumination.

Using values of p, evaluated from the slopes of $\ln(I_0/I_t)$ versus time t plots, under different conditions, shown in Fig. 1, and S, in the relation (5), the trap depths at different ambient conditions were calculated. The different values of trap depths are also systematically presented in the Table 1. From Fig. 1, it is observed that there exist two different slopes in the $\ln(I_0/I_t)$ versus time t plots, which clearly indicates the existence of two distinct trap levels, E_1 and E_2, at any ambient temperature.

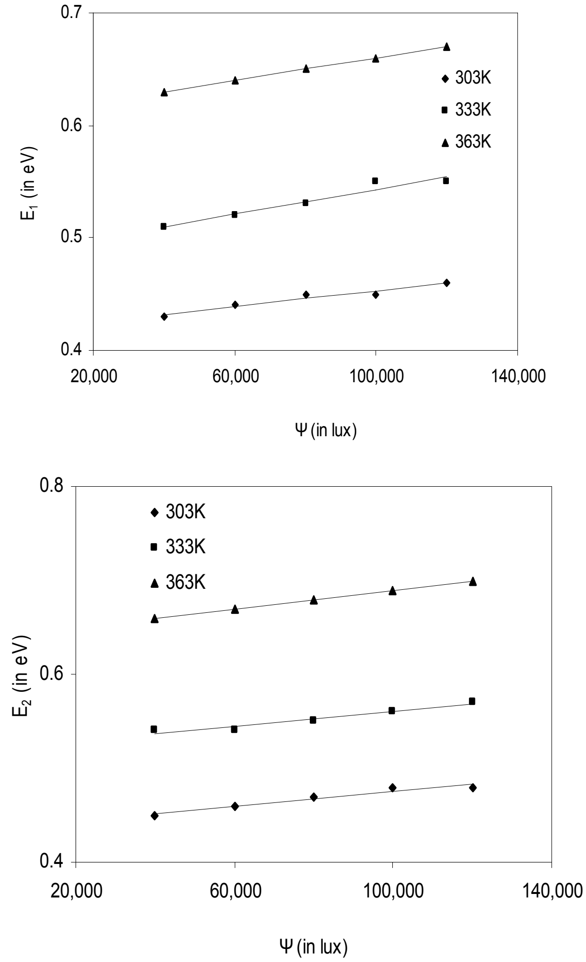

Fig. 3. Trap depth versus intensity of illumination (Ψ) at different ambient temperatures of a CdSe thin film grown at elevated T_s = 473 K.

From X-ray diffraction analysis it was observed that the CdSe thin films grown at room temperature were amorphous and those grown at elevated T_s were of polycrystalline nature having hexagonal ZnS type structure. For the present experimental work of trap depth analysis, only the polycrystalline films were taken into consideration. The polycrystalline thin film consists of grains of various sizes along different orientations and the grain boundaries separating the grains are disordered regions. As already mentioned such films are generally accompanied by different type of defects. It may be noted that photocurrent in these polycrystalline CdSe thin films was found to obey a sub-linear relation with the intensity of illumination which could be explained on the basis of defect controlled photoconductivity mechanism [20, 21] and the estimated trap levels in the present work are likely to be the defect levels.

The depth E, which a trap required to posses in order that an electron may be trapped in it for certain time interval, varies with depth of the trap. Hence the number of traps in which an electron spends a mean time, t, will vary with temperature and therefore I_t varies with temperature. Fig. 2 shows the variation of trap energy with temperature. It is clear from the figures that trap depths E_1 and E_2 are not single valued but varies over a range with temperature.

The traps may be emptied by the utilization of thermal energy as well as by the absorption of optical radiation of different intensity. So the trap depth can be calculated from the spectrum of photoconductivity decay curve. The filled traps are emptied after shutting down the illumination, at a rate depending upon their cross section, lifetime and ionization energy. Thus the decay time becomes different depending upon the trap depth. Figure 3 shows the variation of trap energy with the intensity of white light illumination at different ambient temperature conditions.

4. Conclusions

In thermally deposited CdSe thin films trapping centers are responsible for controlling the photocurrent. Both shallow and deep traps are found to be available in these films. From the evaluated values of trap depth (E), it is seen trap depths E_1 and E_2 are not single valued and there is a quasi-continuous distribution of trap levels below the conduction band. The trap depths have significant variation with both ambient temperature and intensity of white light illumination.

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