

CHAPTER-V

SPECTRAL RESPONSE AND RISE AND DECAY OF PHOTOCURRENT

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5.1. INTRODUCTION

The photoconductivity of a material is a function of intensity and wavelength of the incident radiation. The studies on the dependence of photocurrent on intensity and wavelength of the incident radiations give informations regarding the recombination mechanism, intrinsic and extrinsic band gaps of the material. The rise and decay of photoconductivity provide the additional informations about the trap levels, capture cross sections and also about the trap distribution within the band gap.

When a photoconductor is exposed to light radiation, the photocurrent takes some time called the growth time to reach the maximum or steady state. Again when the light is turned off the photocurrent decays to reach the initial dark value within another interval of time which is called the decay time.

The growth and decay processes in a photoconductor are understandable in terms of processes of release of extra electrons and holes under illumination followed by their recombination /1/. When a

photoconductor is exposed to radiation having photon energy $h\nu \geq E_g$, the intrinsic band gap, electron hole pairs are generated and their densities tend to increase with illumination time. However increase of excess carrier density is controlled by the recombination process as it counterbalances the generation process. After a lapse of time, a steady state is established when the recombination rate equals the generation rate. As the light is turned off the photocurrent decays due to recombination.

The presence of trap plays a significant role in the control of growth and decay of photocurrent. Traps are the regions of crystalline material which are able to capture electrons and holes and detain them in restricted volume. A polycrystalline thin film is composed of grains of various sizes and orientations. The grain boundaries separating the grains are disordered regions and contain trapping centres. When the sample is exposed to radiations a certain proportion of optically generated free carriers is captured by these traps. These filled traps will be emptied after switching off the light at a rate depending upon their cross-section and ionization energy. Thus the decay time will be different depending upon the trap depth, trap distribution etc. In this chapter the rise and decay characteristics of CdTe thin films for different incident light intensity and applied voltage for films of different thickness and also for films grown

at different T_s have been discussed.

5.2. EXPERIMENTALS

For the study of spectral response, Carl Zeiss (GDR) metal interference filters were used for obtaining the monochromatic radiations. The optical illumination was provided by a 250 W tungsten - halogen lamp operating at 24 Volt. A set of metal interference filters having wavelength within the range 400 – 1000 nm was used. The intensity of light was measured with the help of a sensitive lux meter (APLAB, model 5011S). A constant photon flux density for each selected wavelength was used by keeping the intensity fixed at 32 lx in the experiment. The photocurrent was measured using an ECIL (EA 815) electrometer amplifier as described in chapter-II. Since the experimental CdTe films were of very high dark resistivity, care was taken to suppress the electrical noise generated by other sources. To eliminate the effect of stray radiations, observations were recorded at complete darkness, preferably at night. The optical transmittance of the films within the wavelength range 400 – 900 nm was recorded using a double beam spectrophotometer (HITACHI - U-3210). The glass plate used as substrate for deposition of the films was used as reference.

The growth and decay of photocurrent was investigated at different illumination levels, bias voltages and at different temperatures. The growth of current was observed by exposing the sample to light with the help of a mechanical shutter and simultaneously recording the d.c. current for a time period. The light was cut off after some time of reaching steady state and the decay of current with time was again recorded.

For observations of photoconductivity rise and decay at low temperature, the sample holder was kept inside a liquid nitrogen Dewar flask. The Dewar was of corning glass and double walled (Fabricated by NPL, New Delhi) having inner diameter of 55 mm and of length 61 cm.

The details of low temperature arrangement and photoconductivity measurements have already been described in chapter-II.

5.3. RESULTS AND DISCUSSIONS

5.3.1. SPECTRAL RESPONSE

Figure 5-1 shows the spectral response of photoconductivity in films of thickness 1400\AA and grown at different substrate temperatures 27°C , 100°C , 150°C , 200°C and 300°C . It is seen that there is a sharp peak at 750 nm and the peak height increases with increasing T_s . Figure 5-2 shows another spectral response of photoconductivity in films of different

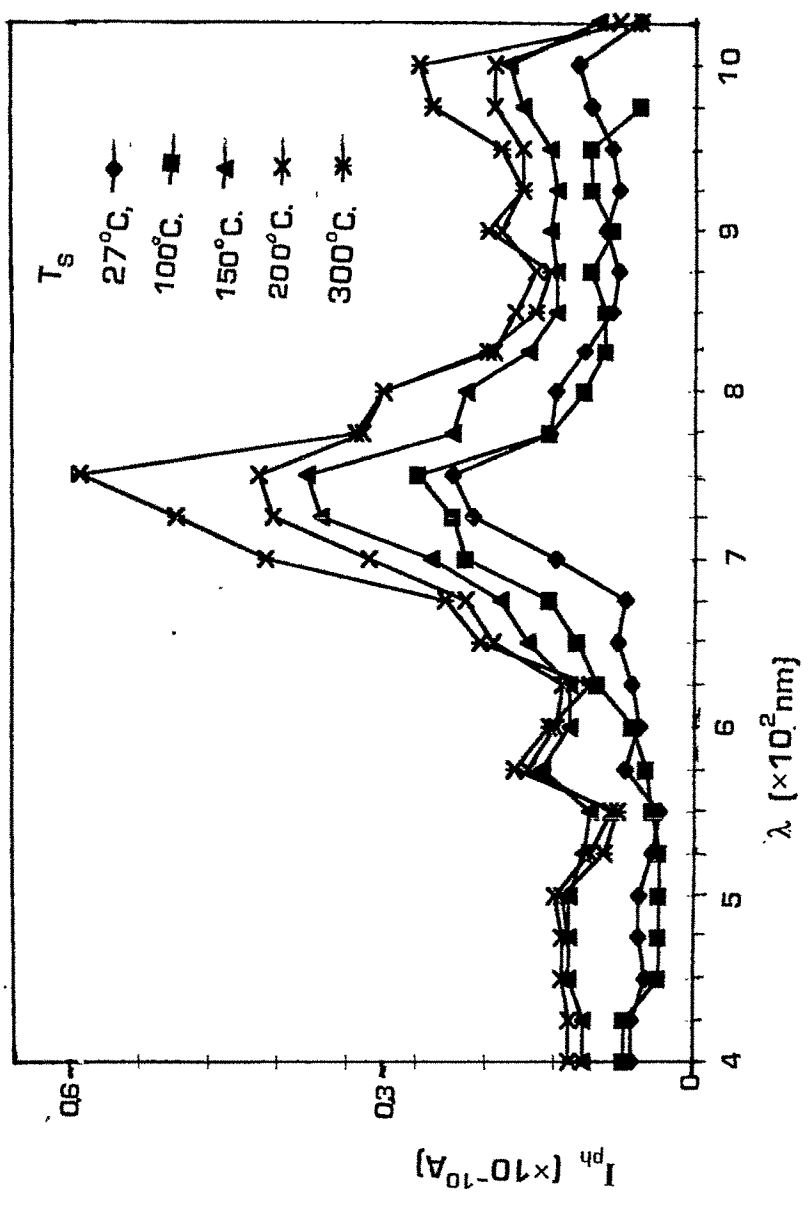


Fig. 5-1. I_{ph} vs λ curves for films of thickness 1400 Å and grown at different T_s .

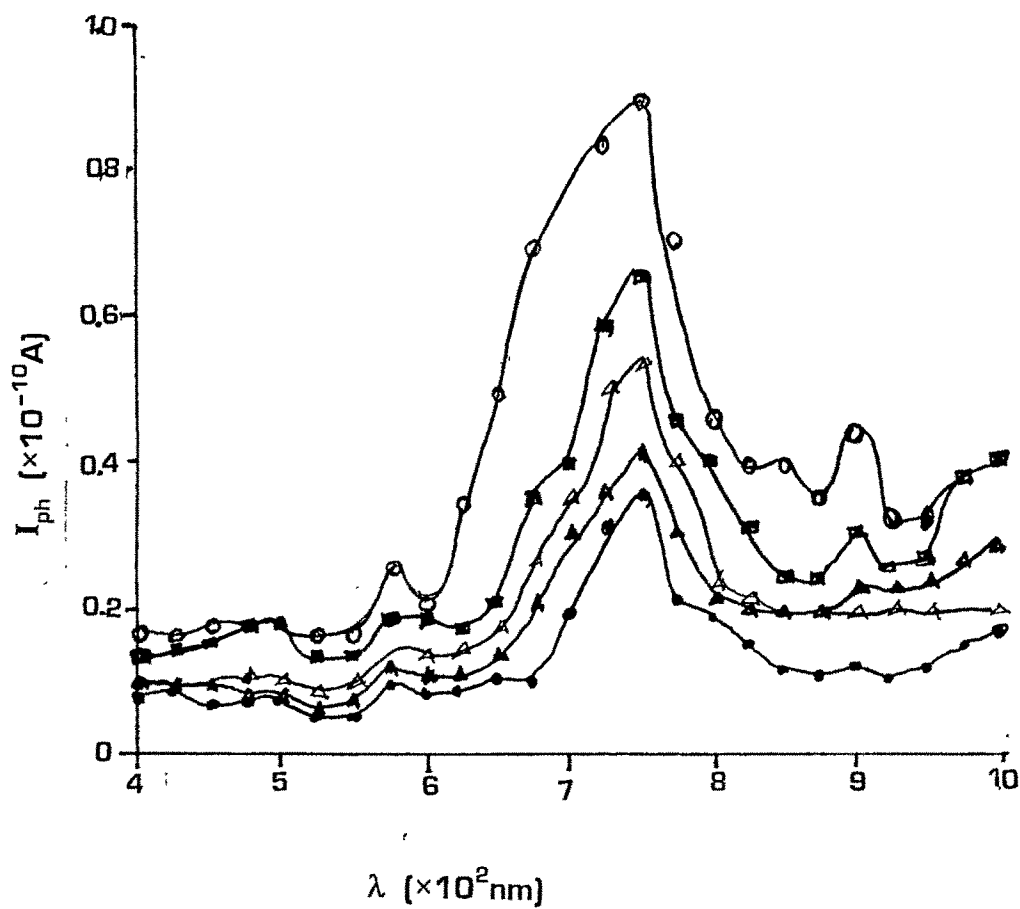


Fig. 5-2. I_{ph} vs λ plots for films of different thickness and grown at $T_s = 300^\circ\text{C}$.

- thickness (t) = 2000Å
- ▲ $t = 2550\text{Å}$
- △ $t = 2950\text{Å}$
- $t = 3900\text{Å}$
- $t = 6500\text{Å}$

thicknesses but grown at same $T_s = 300^\circ\text{C}$. Similar sharp peak is seen at 750 nm and also the peak height of photocurrent increases with increasing thickness. Similar observations in spectral response for different applied bias is shown in figure 5-3. The increase of photocurrent with increase of T_s and thickness is mainly due to increase of grain size and corresponding decrease of grain boundary barrier heights in these films. The maximum spectral sensitivity of CdTe films at 750 nm corresponds to an optical energy gap of 1.65 eV. This value of energy gap is close to the band gap energy of CdTe (1.5 eV at room temperature) /2/ single crystal, with a difference of 0.15 eV.

The possible causes of the observed gap shift in the films can be explained from the following mechanism /3/.

(i) Since CdTe have zinc blende type structures, the indirect band gap can not be less than the direct band gap. Thutupalli and Tomlin /4/ have reported that CdTe thin film deposited at different T_s (20°C to 300°C) have indirect band gap value between 1.76 eV to 1.81 eV.

(ii) It is known that in presence of high density of defects, charged impurities and disorder at the grain boundaries, transition rules are relaxed due to the internal electric field developed at the grain boundaries. This field may cause a shift in the band edge and gives rise to an optical

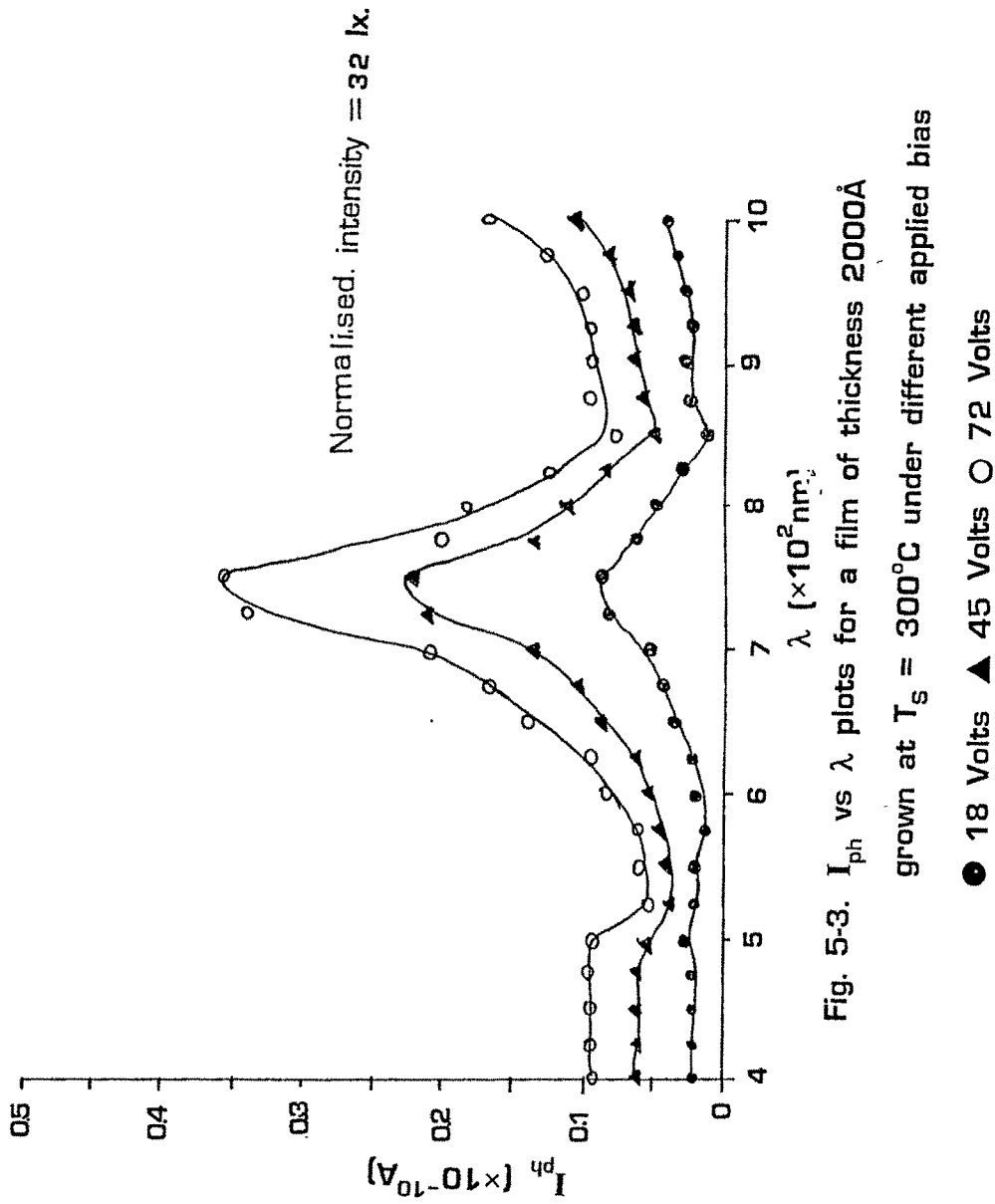


Fig. 5-3. I_{ph} vs λ plots for a film of thickness 2000Å grown at $T_s = 300^\circ C$ under different applied bias

transition with photon energy less than the direct band gap energy.

Considering zinc blende type of structure of the experimental films as discussed in chapter III and a higher value of 1.65 eV in the observed gap width, it can be inferred that indirect transition takes place in the films.

From figures 5-1 – 5-3 it is also seen that photocurrent decreases for shorter wavelength. The shorter wavelengths have higher photon energy and are being strongly absorbed produces excitation only near the thin surface layer of the film. Since the volume of this layer is small, the concentration of free carriers (both electrons and holes) in it become very high which causes sharp increase in recombination rate and hence a decrease in the surface life time. The increase in the recombination rate is also facilitated by the presence of various impurities and defects in the surface layer which act as recombination centres /5/. Thus due to high surface recombination the photocurrent (I_{ph}) is smaller when the film is excited by light of shorter wavelength than the band edge wavelength.

The decrease of photocurrent for longer wavelengths in the spectral response is usually explained on the basis of high transmittance of light (i.e. low absorbance) for longer wavelengths beyond 750 nm. The high transmittance and low absorbance for longer wavelengths of two representative CdTe films grown at $T_s = 300^\circ\text{C}$ and thickness 3900Å and

6500Å respectively are shown in figure 5-4 and figure 5-5.

5.3.2. GROWTH AND DECAY

Growth and decay times of photocurrent can be analysed from the following considerations /6/. The recombination rate of excess carriers in the CdTe films is given by the formula

$$R_p = \frac{\Delta p}{t} \quad \dots [1a]$$

$$\text{and} \quad R_n = \frac{\Delta n}{t} \quad \dots [1b]$$

Where Δp and Δn are the densities of excess carriers (holes and electrons) and t the photoconductivity growth time.

The total change in the number of excess carriers in a given time interval is the sum of the rates of their formation and recombination /5, 7/

$$\frac{d}{dt}(\Delta p) = G_p + R_p - \alpha \eta J \frac{\Delta p}{t} \quad \dots [2a]$$

$$\frac{d}{dt}(\Delta n) = G_n + R_n - \alpha \eta J \frac{\Delta n}{t} \quad \dots [2b]$$

Where G_p or G_n is the rate of carrier formation, η is the photo-ionization quantum yields (efficiencies) which determines the average number of electron-hole pairs generated by a quantum ($h\nu$) of radiant energy, α is the light absorption coefficient and J is the light intensity.

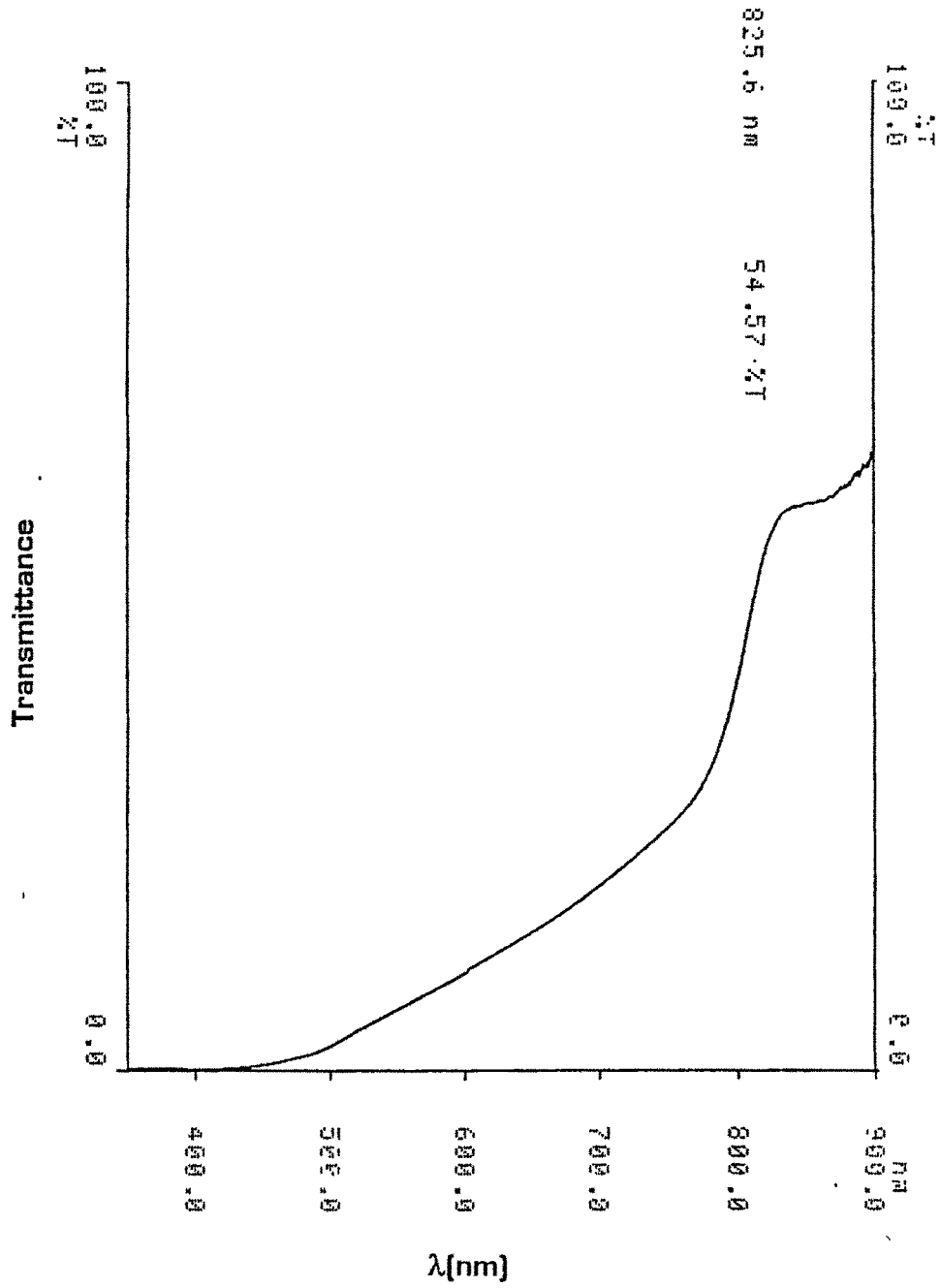


Fig. 5-4. Transmittance vs λ plots for a film of thickness 3900\AA grown at $T_s = 300^\circ\text{C}$

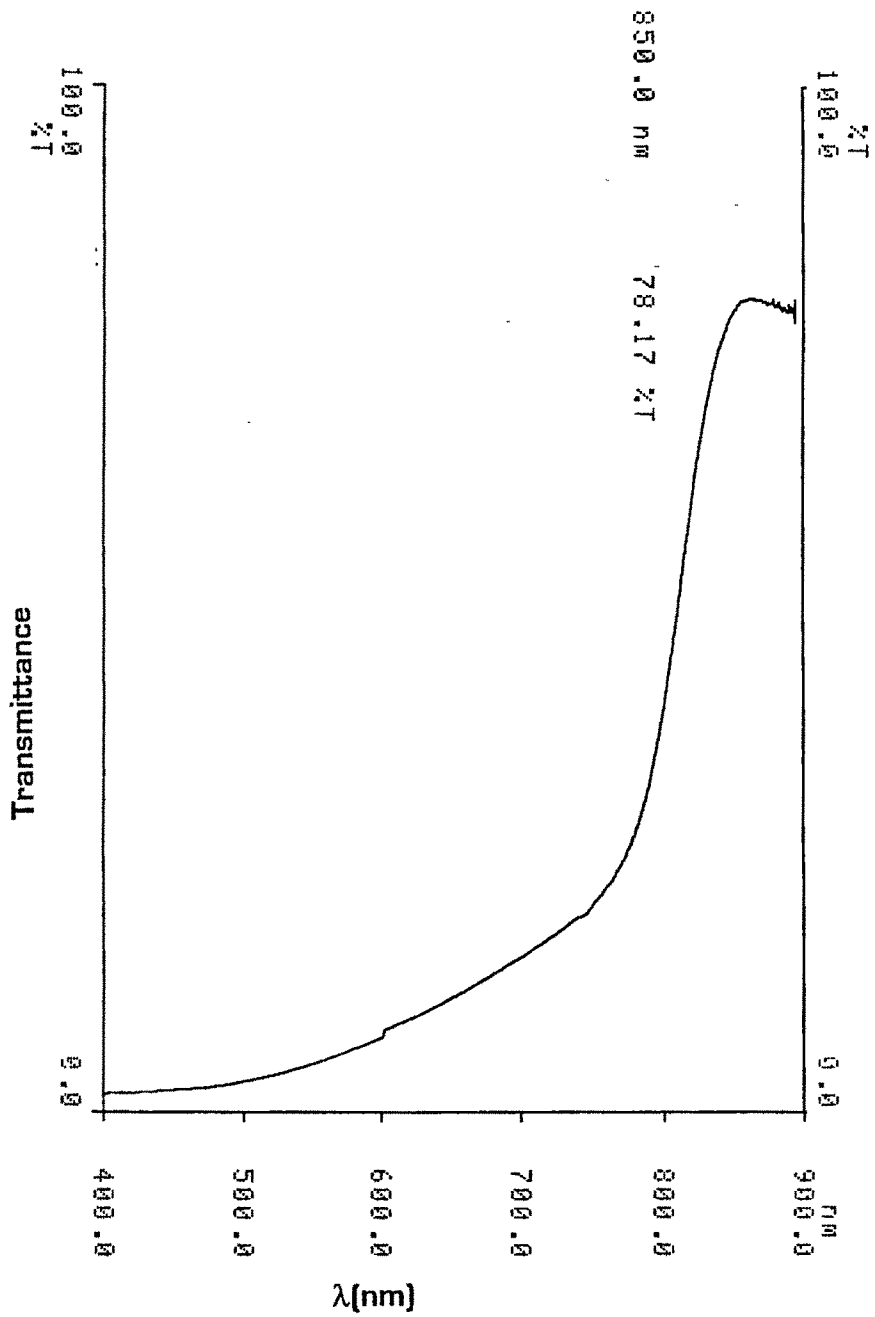


Fig. 5-5. Transmittance vs λ plots for a film of thickness 6500Å grown at $T_s = 300^\circ\text{C}$.

For growth of current at $t = 0$

$$\Delta p = 0 \quad \dots (3)$$

and from the solution of equation (2a) for the above condition,

$$\Delta p = \alpha \eta J \mathcal{T} \left\{ 1 - \exp\left(-\frac{t}{\mathcal{T}}\right) \right\} \quad \dots (4a)$$

$$\text{Similarly, } \Delta n = \alpha \eta J \mathcal{T} \left\{ 1 - \exp\left(-\frac{t}{\mathcal{T}}\right) \right\} \quad \dots (4b)$$

Here \mathcal{T} is the growth time in equations 4a and 4b.

The time dependence of the growth of photoconductivity σ_t is given by—

$$\sigma_t = q \mu \alpha \eta J \mathcal{T} \left\{ 1 - \exp\left(-\frac{t}{\mathcal{T}}\right) \right\} \quad \dots (5a)$$

When q and μ are the charge and mobility of the carriers respectively.

For $t = 0$, $\sigma_t = 0$ and for $t \rightarrow \infty$, $\sigma_t = q \mu \alpha \eta J \mathcal{T} = \sigma_0$ and we get from equation (5a)

$$\sigma_t = \sigma_0 \left\{ 1 - \exp\left(-\frac{t}{\mathcal{T}}\right) \right\} \quad \dots (5b)$$

The plot of the function given by equation (5b) for the growth of the current will yield a curve as shown in figure 5.6. The tangent to this curve at the origin of the co-ordinate system intercepts the straight line $\sigma = \sigma_0$ at $t = \mathcal{T}$, corresponding to the photoconductivity growth time.

After a lapse of time when the photocurrent reach the steady state value the light is turned off and then the photocurrent begins to decrease.

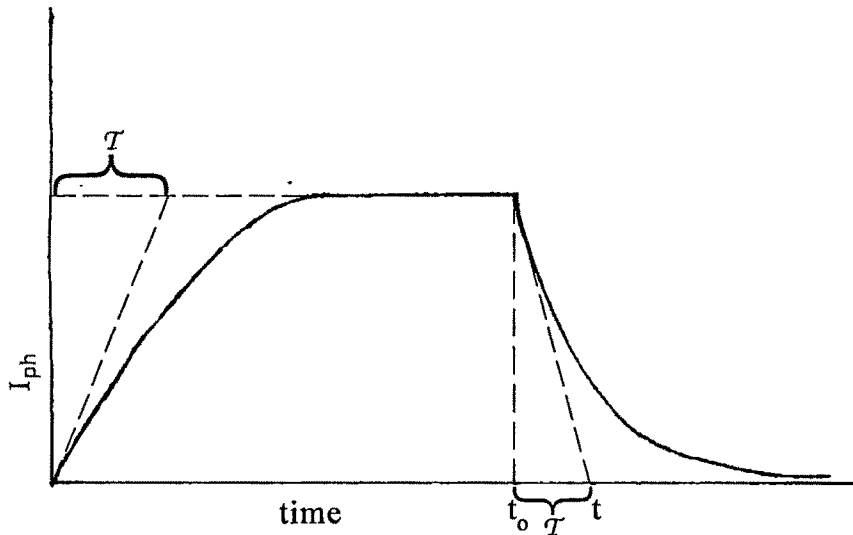


Fig.5-6 The growth and decay of photocurrent of a photoconductor after turning on and off the light.

The change in the number of excess carriers occurs as a consequence of their recombination. Hence

$$\frac{d}{dt}(\Delta p) = -\frac{\Delta p}{\mathcal{T}} \quad \dots [6]$$

If the origin of the scale is taken at t_0 (as shown in fig. 5.6) for decay process, then at the instant of turning off the light we obtain from equation (4a), by considering the fact that $t_0 > \mathcal{T}$, the concentration of excess carriers become—

$$\Delta p = \alpha \eta J \mathcal{T} \quad \dots [7]$$

Putting this condition [7] in equation [6] yields the solution of the equation—

$$\Delta p = \alpha \eta J \mathcal{T} \exp\left(-\frac{t}{\mathcal{T}}\right) \quad \dots [8]$$

Thus, $\Delta p q \mu = q \mu \alpha \eta J \mathcal{T} \exp\left(-\frac{t}{\mathcal{T}}\right)$

$$\sigma_t = \sigma_0 \exp\left(-\frac{t}{\mathcal{T}}\right) \dots [9]$$

The second part of the curve in Fig.5.6 is obtained by plotting the function given by equation (9). The decay time is obtained by drawing the tangent to the curve at the point t_0 and intercepts the time axis at t gives the decay time $\mathcal{T} = t - t_0$.

Figures 5.7 – 5.9 show the curves of experimentally observed rise and decay of photocurrent as a function of time for films grown at different T_s of 150°C , 200°C and 300°C and of thickness 1400 Å. Each set of curve represents the growth and decay characteristics for three different intensities observed at low temperature 93 K and for constant applied bias as indicated. The sample is kept at low temperature to avoid thermal trap emptying process. The nature of the curves are similar to that shown in figure 5.6 obtained from theoretical plot. Thus the rise and decay characteristics in the films can be explained on the basis of generation of excess carrier due to photon absorption for $h\nu \geq E_g$ as is seen from the absorption spectrum mentioned earlier, followed by their recombination. Both bimolecular and monomolecular recombination predominate in our experimental films and has been discussed previously (chapter-IV).

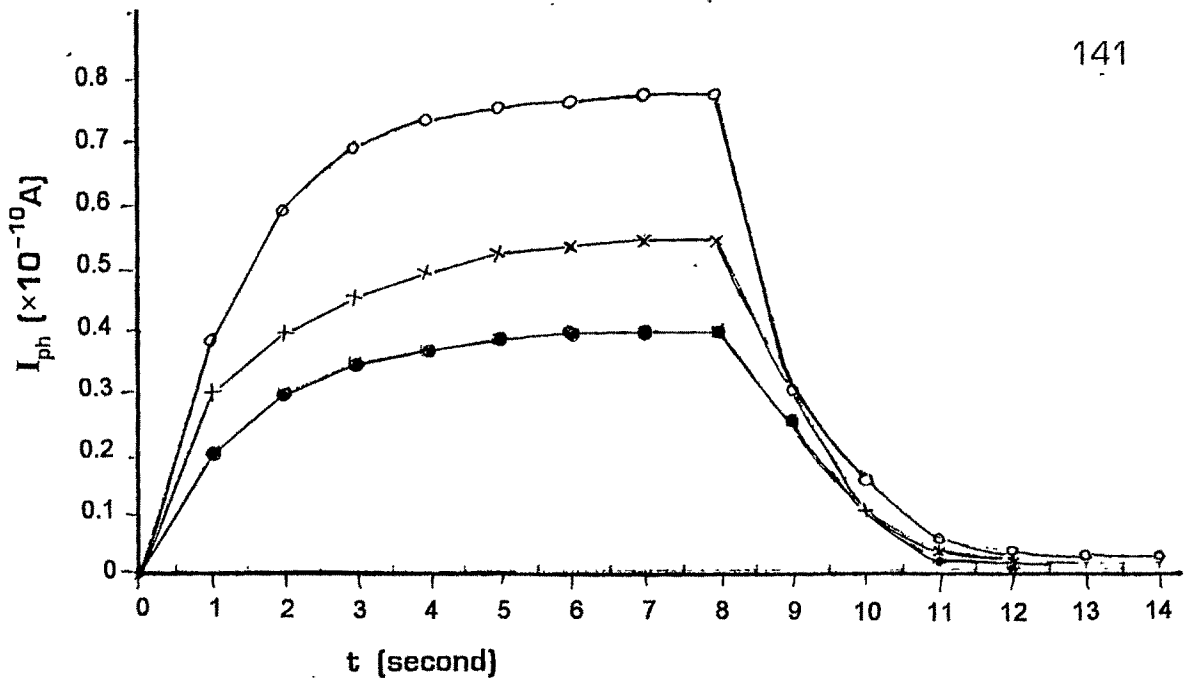


Fig. 5-7. Rise and decay of I_{ph} with time at 93 K for a film of thickness 1400Å grown at $T_S = 150^\circ\text{C}$. Applied bias = 45 Volts.

● Intensity 7000 lx X Intensity 10500 lx ○ Intensity 15000 lx

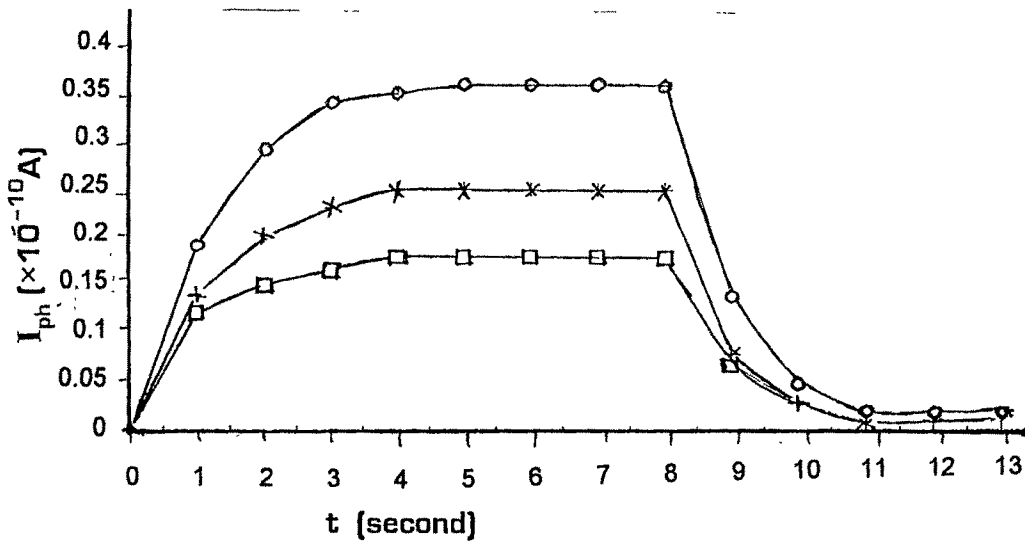


Fig. 5-8. Rise and decay of I_{ph} with time at 93 K for a film of thickness 1400Å grown at $T_S = 200^\circ\text{C}$. Applied bias = 45 Volts.

□ Intensity 7000 lx X Intensity 10500 lx ○ Intensity 15000 lx

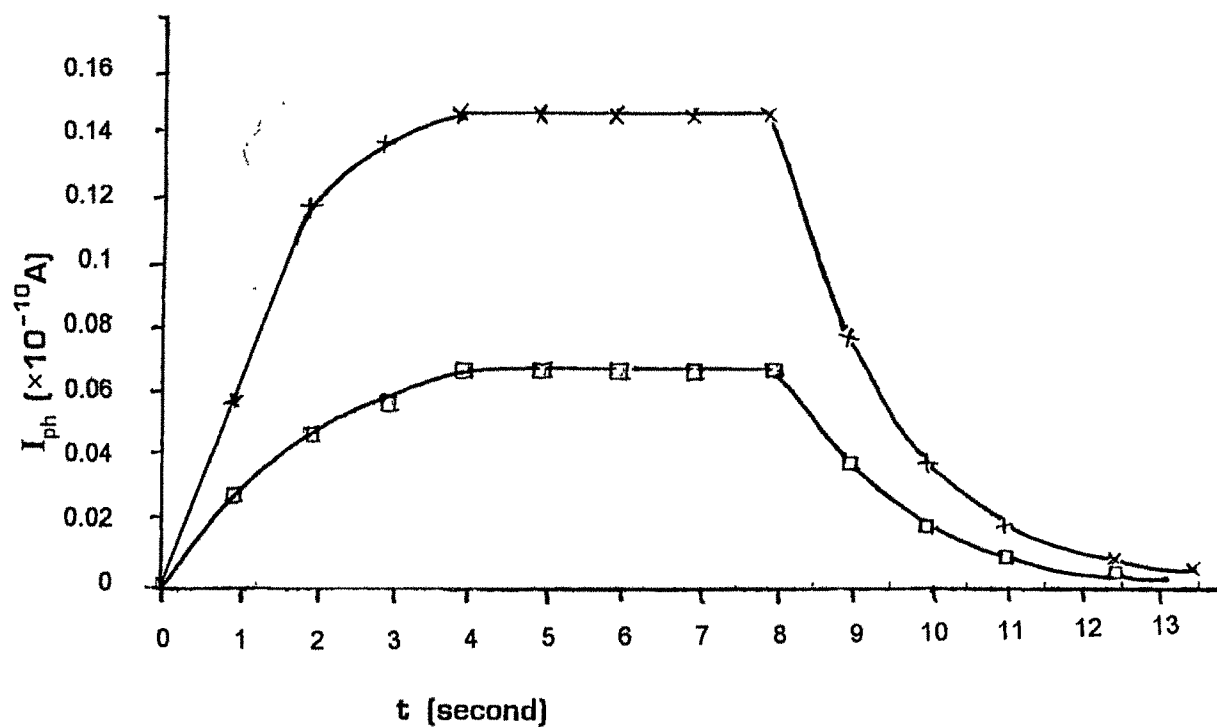


Fig. 5-9. Rise and decay of I_{ph} with time at 93 K for a film of thickness 1400Å grown at $T_s = 300^\circ\text{C}$. Applied bias = 18 Volts.

□ Intensity 7000 lx

X Intensity 15000 lx

From the observations of variation of photocurrent with light intensity [discussed in chapter IV] the observed values of γ from the relation $I_{ph} \propto \phi^\gamma$, where ϕ is the intensity of the incident light and γ is an intensity parameter lies between 0.5 to 1. This is in accordance with the picture of traps being present in the energy gap in the band model leading to the charge carrier production by exciton process. The values of γ observed in the range of $0.5 < \gamma < 1.0$ for the CdTe films (chapter IV, table 1) clearly indicates the presence of defect states in the material /7/. The sublinear behaviour can be interpreted in terms of cooperation between the traps and the recombination centre.

The calculated values of rise time (\mathcal{T}_r) and decay time (\mathcal{T}_d) is shown in table 1. It is seen that \mathcal{T}_r and \mathcal{T}_d decrease with increasing intensity. At high illumination the number of free carrier is much greater than the number of trapped carriers and hence electrons recombine with holes without significantly involving trapping processes /8/. The rise and decay times are also found to be dependent on the temperature, film thickness and applied bias, Figures 5-10 — 5-11 show the rise and decay characteristics of CdTe films of various thickness and for different applied bias. The calculated values of \mathcal{T}_r and \mathcal{T}_d are shown in tables 2, 3 and 4. The rise and decay times are found to be slightly dependent on film

Table 1

Values of rise time (τ_r) and decay time (τ_d) of CdTe films deposited at different T_s and observed at low temperature 93 K for different intensity of illumination.

Film grown at T_s °C	Film thickness (Å)	Applied bias (volts)	Intensity of illumination (lx)	τ_r (second)	τ_d (second)
150	1400	45	7000	1.6	0.8
			10500	1.5	0.6
			15000	1.4	0.5
200	1400	18	7000	1.1	0.7
			10500	1.1	0.6
			15000	0.9	0.5
		45	7000	1.5	0.6
			10500	1.3	0.3
			15000	1.2	0.3
300	1400	18	7000	1.6	0.8
			15000	1.4	0.7

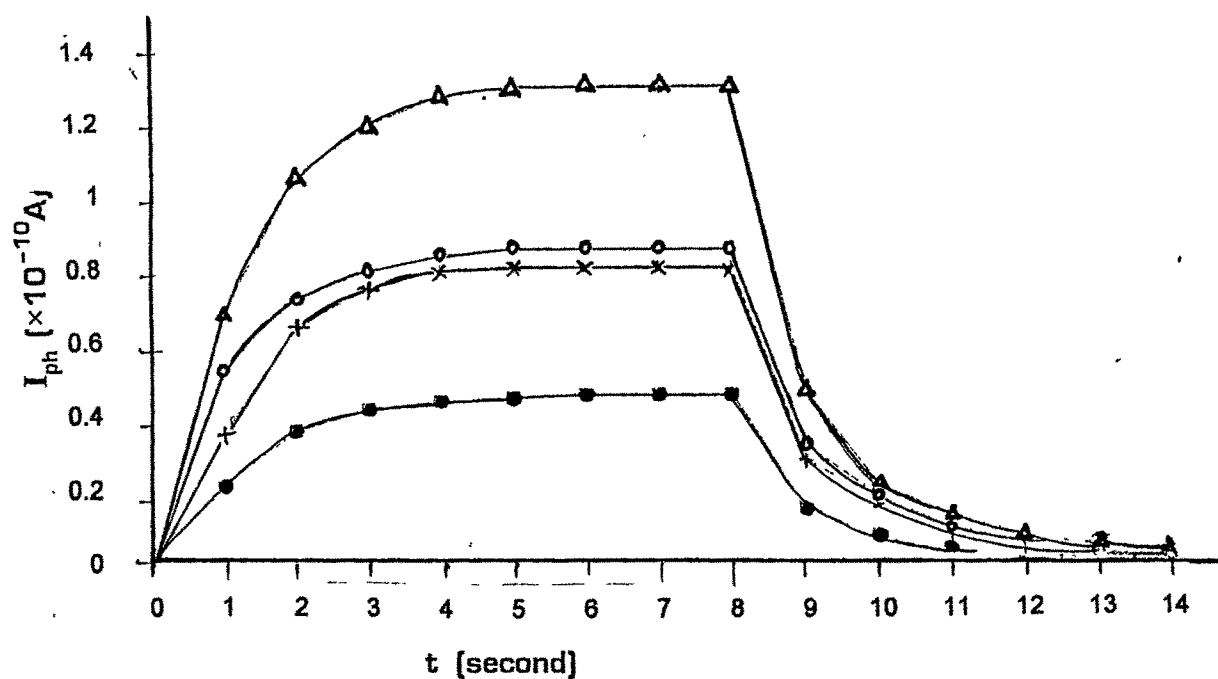


Fig. 5-10. Rise and decay of I_{ph} with time at 28°C for films of different thickness grown at $T_s = 300^{\circ}\text{C}$. Applied bias = 18 Volts. Intensity = 4000 lx

● 2000Å X 2950Å ○ 3900Å △ 6500Å

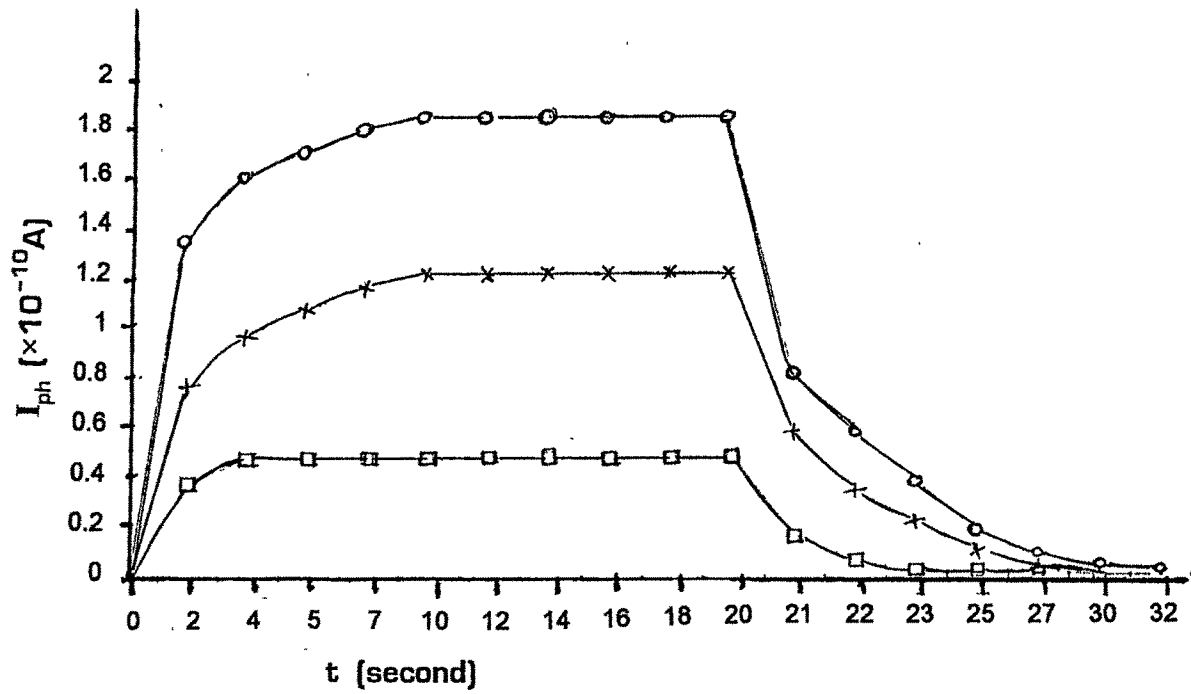


Fig. 5-11. Rise and decay of I_{ph} with time for a film of thickness 1400\AA grown at $T_s = 200^\circ\text{C}$. Intensity = 7000 lx . Observed at 28°C .
 \square 18 Volts \times 45 Volts \circ 72 Volts

Table 2

Values of rise time (τ_r) and decay time (τ_d) of CdTe films of different thickness grown at $T_s = 300^\circ\text{C}$ at constant intensity of illumination. (observations were made at room temperature)

Film grown at $T_s^\circ\text{C}$	Applied bias (volts)	Intensity of illumination (lx)	Film thickness (\AA)	τ_r (second)	τ_d (second)
300	18	4000	2000	1.4	0.6
			2950	1.3	0.4
			3900	1.2	0.4
			6500	1.2	0.4

Table 3

Values of \mathcal{T}_r and \mathcal{T}_d of two films of different thickness grown at $T_s = 300^\circ\text{C}$ and at three different intensity of illumination. (observations were made at room temperature)

Film grown at $T_s^\circ\text{C}$	Applied bias (volts)	Film thickness (\AA)	Intensity of illumination (x)	\mathcal{T}_r (second)	\mathcal{T}_d (second)
300	18	1400	4000	1.75	1.25
			7000	1.5	0.75
			10500	1.5	0.5
		6500	4000	1.4	0.6
			7000	1.3	0.5
			10500	1.2	0.5

Table 4

Values of \mathcal{T}_r and \mathcal{T}_d of a CdTe film at a constant intensity of illumination and a different applied bias. (observations were made at room temperature)

Film grown at $T_s^\circ\text{C}$	Film thickness (\AA)	Intensity of illumination (lx)	Applied bias (volts)	\mathcal{T}_r (second)	\mathcal{T}_d (second)
200	2000	7000	18	1.5	0.5
			45	2.0	0.5
			72	1.5	0.5

thickness and independent of applied bias. The higher value of rise and decay time obtained in the films indicate large ratios of concentrations of filled traps and free carriers due to illumination in the equation for time constant of rise and decay of photocurrent /9/.

$$\mathcal{T}_{o(n)} = \left(1 + \frac{n_t}{n}\right) \mathcal{T}_n \quad \dots (10a)$$

$$\mathcal{T}_{o(p)} = \left(1 + \frac{p_t}{p}\right) \mathcal{T}_p \quad \dots (10b)$$

Where n_t or p_t is the electron or hole density, in the traps, n or p is the free carrier density and \mathcal{T}_n and \mathcal{T}_p is the electron or hole life time. The slow release of trapped charge carriers increases the decay time. The presence of deep traps is also evident from this fact. To confirm the presence of deep trap in the films $\log I_{ph}$ is plotted against $\log t$ for photoconducting decay in films of different thickness and deposited at $T_s = 300^\circ\text{C}$. Figures 5.12 – 5.15 show $\log I_{ph}$ vs $\log t$ plots for photoconducting decay at three different intensities. The time dependent decay curve can be expressed generally as /10/.

$$I_t = I_0 t^{-b} \quad \dots (11)$$

Where I_t is the photocurrent at time t after switching off the light, I_0 is the initial value of photocurrent at $t = 0$ and b is a dimensionless quantity called the decay constant. For each intensity there are two linear regions

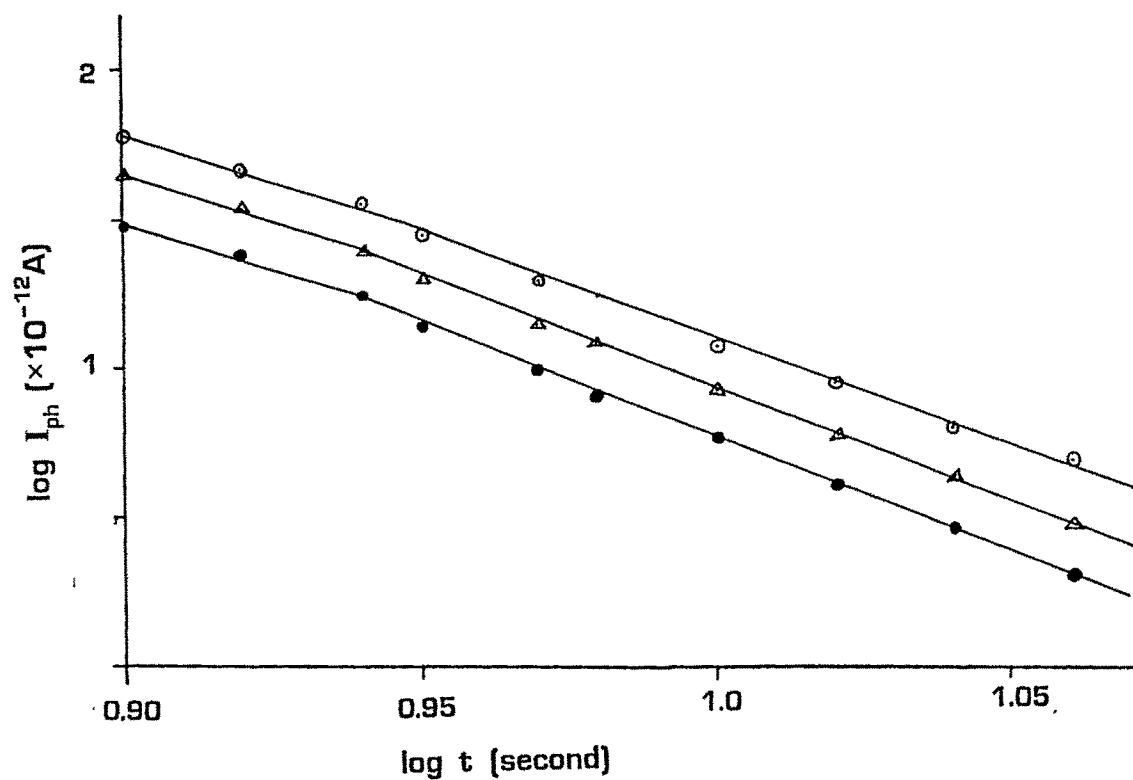


Fig. 5-12. $\log I_{ph}$ vs $\log t$ plots. Film thickness = 2550 \AA , $T_s = 300^\circ \text{C}$.

● Intensity = 4000 lx

△ Intensity = 7000 lx

○ Intensity = 10500 lx

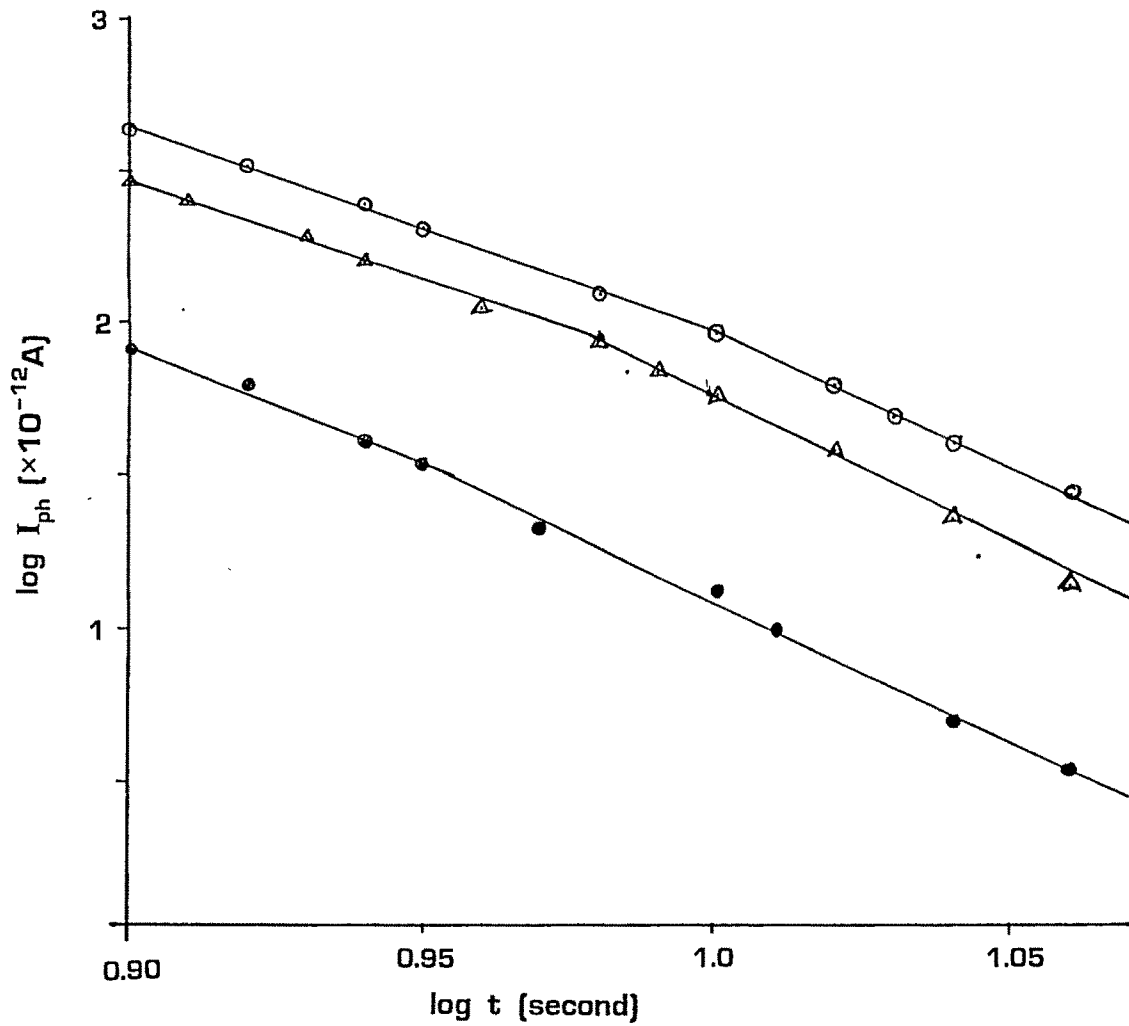


Fig. 5-13. Log I_{ph} vs log t plots. Film thickness = 2950\AA , $T_s = 300^\circ\text{C}$.

- Intensity = 4000 lx
- △ Intensity = 7000 lx
- Intensity = 10500 lx

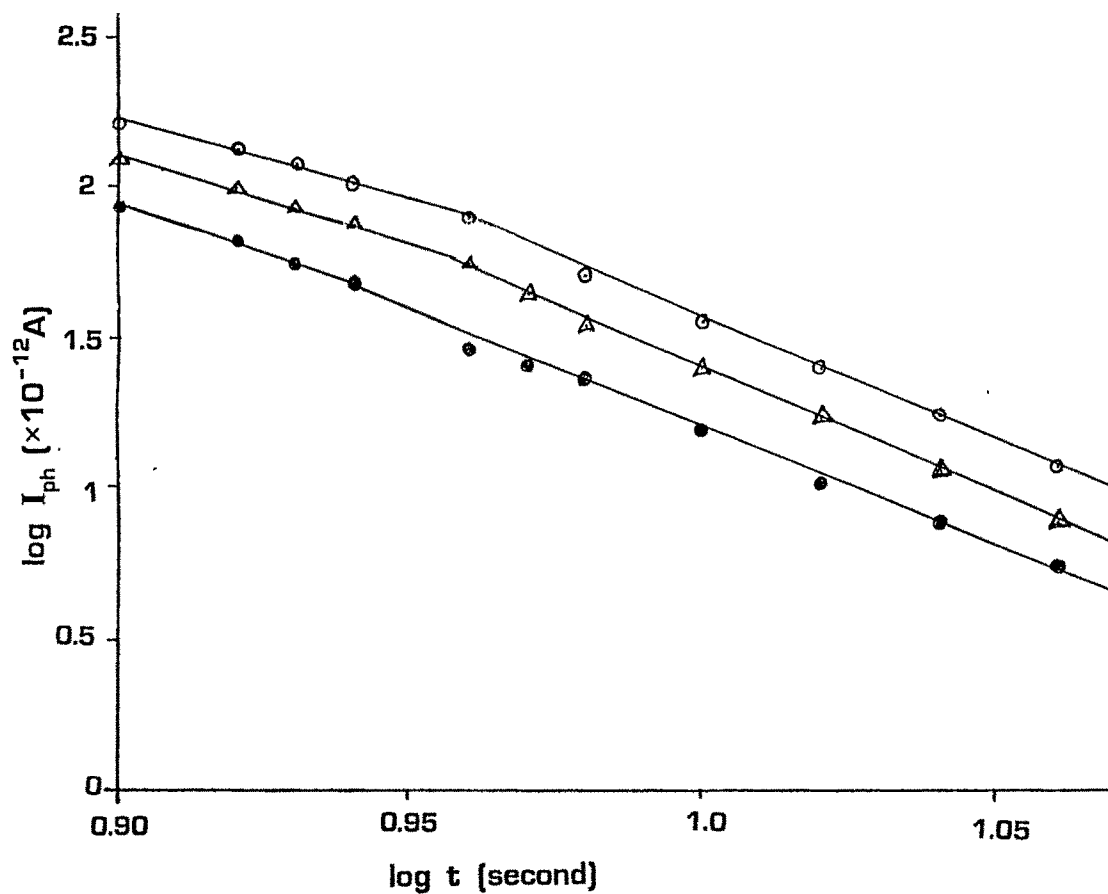


Fig. 5-14. Log I_{ph} vs log t plots. Film thickness = 3900\AA , $T_s = 300^\circ\text{C}$.

- Intensity = 4000 lx
- △ Intensity = 7000 lx
- Intensity = 10500 lx

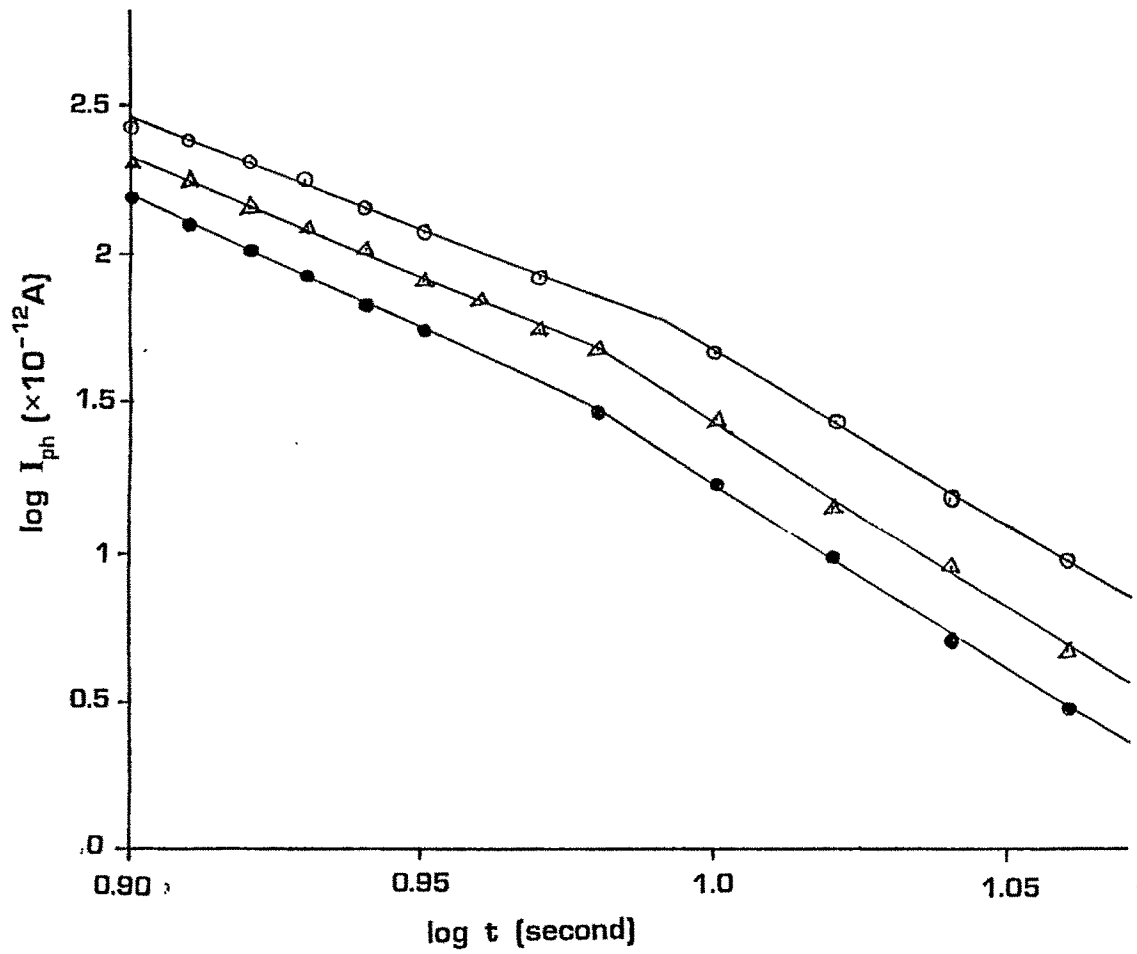


Fig. 5-15. Log I_{ph} vs log t plots. Film thickness = 6500\AA , $T_s = 300^\circ\text{C}$.

● Intensity (ϕ) = 4000 lx

△ $\phi = 7000$ lx

○ $\phi = 10500$ lx

obeying the above relation. The region I is associated with shallow traps while region II is due to deep traps. The trap depth E_t below the bottom of the conduction band or above the top of the valence band can be calculated by using the decay law /11/.

$$I_t = I_0 \exp (-Pt) \quad \dots [12]$$

Where P is the probability of escape of an electron from the trap per second, is given by

$$P = S \exp (-E_t/kT) \quad \dots [13]$$

Where S is the frequency factor defined in terms of the number per second that the quanta from crystal vibrations (phonons) attempt to eject the hole (electron) from the trap, multiplied by the probability of transition from the trap to the conduction or valence band. For most of the photoconductors the value of S is taken to be 10^9 per sec. From equations (12) and (13) the expression for E_t comes out to be

$$E_t = kT \left[\log_e S - \log_e \frac{\log_e(I_0 / I_t)}{t} \right] \quad \dots [14]$$

The value of trap depth E_t thus calculated for films of different thickness but deposited at the same substrate temperature, $T_s = 300^\circ\text{C}$ and at different intensities are shown in table 5 and for films of same thickness 1400\AA but deposited at different T_s are shown in table 6. The

Table 5

Values of trap depths E_t calculated from the decay curves of some CdTe films with different thickness grown at $T_s = 300^\circ\text{C}$.

Film grown at $T_s^\circ\text{C}$	Film thickness (\AA)	Trap depth below the conduction band (eV)		
		At intensity 4000 lx.	At intensity 7000 lx.	At intensity 10500 lx.
300	2000	0.535	0.537	0.539
	2550	0.539	0.539	0.54
	2950	0.54	0.54	0.54
	3900	0.53	0.54	0.543
	6500	0.537	0.538	0.543

Table 6

Values of trap depths E_t calculated from the decay curves of some films grown at different T_s and of same thickness.

Film thickness (Å)	Film grown at $T_s^\circ\text{C}$	Trap depth below the conduction band (eV)		
		At intensity 4000 lx.	At intensity 7000 lx.	At intensity 10500 lx.
1400	27	0.637	—	—
	150	—	0.585	—
	200	0.553	0.548	0.538
	300	0.552	0.549	0.54

trap depth E_t is found to be same for films of different thickness and as expected the calculated trap depth E_t is also found to be same at different illumination intensities. The average value of trap depth (from table 5) E_t calculated is 0.54 eV. For films deposited at different T_s and of same thickness 1400Å the trap depth calculated is also found to be 0.55 eV. However for films deposited at room temperature substrate the calculated value of trap depth E_t is found to be 0.64 eV. Similar results have been reported by Sitter et al /12/. The average value of E_t thus calculated is also in good agreement with the previously reported value for CdTe thin films /13/.

SUMMARY :

(1) The spectral response of photoconductivity in vacuum deposited CdTe films shows a maximum sensitivity at 750 nm. The photoconductivity decreases both for longer and shorter wavelength than this wavelength. For shorter wavelength the photoconductivity decreases due to high surface recombination and for longer wavelength the photoconductivity decreases due to increase of percentage of transmission of the incident light beyond the band edge wavelength.

(2) The position of the maximum sensitivity in the spectral response gives the value of optical band gap to be 1.65 eV and corresponds to an indirect transition.

(3) The observations of rise and decay of photocurrent in the CdTe thin films show an initial fast rise followed by a slow increase of photocurrent to reach steady state value. The corresponding decay curve also shows initial fast decrease of photocurrent followed by slow exponential decay.

(4) The rise and decay times of photocurrent are found to be dependent on intensity of illumination, ambient temperature and applied bias voltage.

(5) The photocurrent increases both with increase of T_S of the film deposition and also with increase of thickness of the films for constant T_S of deposition. The increase of photocurrent is mainly due to decrease of defect density and increase of crystallite size with increase of T_S .

(6) The nature of rise and decay curves show that trapping centres are responsible for controlling the photocurrent. Both shallow and deep traps are found to be present in the films. The calculated values of trap depths are found to be similar with some reported values by other workers.

REFERENCES

- /1/ M. Buragohain and K. Barua, Indian J. Phys-61 A (1987) 559-662.
- /2/ F. A. Kroger, The Chemistry of Imperfect crystal, North Holland Publishing Company, Amsterdam, 1964, P669.

- /3/ B. Samanta, S. L. Sharma and A. K. Choudhuri, Indian Journal of Pure and Applied Physics, 32 [1994] PP62 – 67.
- /4/ G. K. M. thutupalli and S. G. Tomlin, J. Phys. D 9 [1976] 1639.
- /5/ P. S. Kireev, semiconductor Physics, MIR Publisher, Moscow, 1978, P492.
- /6/ Z. Porada and E. Schabowska – Thin Solid Films 66 [1980] L55 – L58.
- /7/ A. Rose, Concept in Photoconductivity and Allied Problems, Interscience, New York, 1963.
- /8/ M. Buragohain and K. Barua, Indian J. Phys. 59A, [1985] 178 – 184.
- /9/ H. O. Yadav, T. S. Varadarajan, M. Mohanty, B. N. Pattanaik, L. N. Patnaik, Solar Energy Materials and Solar Cells, 35 [1994] 341 – 346.
- /10/ R. H. Bube, Photoconductivity of Solids, John Wiley & Sons, New York, 1960.
- /11/ B. N. Srivastava and S. Sing, Indian Journal of Pure & Applied Physics, 8 [1970] PP716 – 724.
- /12/ H. Sitter, J. Humenberger, W. Huber and Lopez-Otero, Solar Energy Materials 9 [1983] 199 – 206.
- /13/ C. Lhermitte and C. Vautier, Thin Solid Films, 58 [1979] 83 – 88.

