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FURTHER INVESTIGATION ON THE PHOTODIELECTRIC PROPERTIES OF CdTe THIN FILM

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The samples of the photocapacitors : the electrode (In)-photodielectric (CdTe)—the electrode (In), have been prepared by the method of evaporation under a vacuum of 3×10^{-5} mm Hg. The relative change in the photocapacitor capacity *vs* illumination was studied. The comparison of experimental results with the theoretical ones indicates the possibility of a good application of the model. The concentration of acceptors increases on decreasing the distance giving rise to dielectric loss.

Key Words : Photodielectrics; CdTe Thin Film; Dielectric Loss

INTRODUCTION

CdTe is a particularly interesting group of II-VI materials because the majority carrier type can be changed by controlling the stoichiometry.[1] The most thorough work on photosensitive CdTe has probably been that of Urli[2] who observed increases in the dark resistivity and the creation of centres giving rise to energy levels in the forbidden band after irradiation. Photoconductivity of either *p*-type or *n*-type CdTe samples may be measured by the normal method using steady source of light of a particular wavelength to give a photo-current curve.[3] The dielectric constant of the matter is altered by the light through the easily polarized centres, for instance the electron traps[4] and the space charge among the grain boundaries in polycrystalline materials.

In this paper, a model of photodielectric effect (PDE) is given and compared with the experimental results. The theoretical function $\Delta C/C_0 = f(J_0)$ is compared with the experimental results for thin film photocapacitors. Moreover, the effect of illumination on the dielectric loss is studied.

Nomenclature :

C—Electrical capacity (F).

L_n, D_p—Diffusion coefficients (m^2 sec^{-1}).

E—Electrical field intensity (Vm^{-1}).

e—Charge of free carrier (Asec).

G_n, G_p—Free carrier generation rate (m^3 sec^{-1}).

J_0—Intensity of illumination (Wm^{-2}).

J_n, J_p—Free carrier flow density (Am^{-2}).

k—Boltzmann constant ($J\text{deg}^{-1}$).

n—Free electrons concentration (m^{-3}).

P—Free holes concentration (m^{-3}).

n_0, P_0—Equilibrium concentration (m^{-3}).

Q_v—Optic free carrier generation rate ($m^{-3}\ sec^{-1}$).

Q_t—Thermal free carrier generation rate ($m^{-3}\ sec^{-1}$).

R_n, R_p—Recombination rate ($m^{-3}\ sec^{-1}$).

r—Radius vector (m).

T—Temperature (°K).

α—Absorption coefficient (m^{-1}).

γ—Recombination coefficient ($m^3\ sec^{-1}$).

ϵ—Dielectric constant (Fm^{-1}).

η—Quantum efficiency ($W^{-1}\ sec^{-1}$).

μ_n, μ_p—Free carrier mobility ($m^2V^{-1}\ sec^{-1}$).

σ—Conductivity ($\Omega^{-1}m^{-1}$).

w—Frequency of electric field (sec^{-1}).

THEORY

The current density of the charge carriers J_n, J_p, the electric field intensity E, and the concentration n, p of the free carriers in the intrinsic semiconductor are bound together by the system of the differential equations :

$$J_n = e(\mu_n n E + D_n \nabla n), \qquad \ldots(1)$$

$$J_p = e(\mu_p P E - D_p \nabla p), \qquad \ldots(2)$$

$$\nabla \cdot E = \frac{e}{\epsilon}(P - n), \qquad \ldots(3)$$

$$\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{e}\nabla \cdot J_n \qquad \ldots(4)$$

and

$$\frac{\partial P}{\partial t} = G_p - R_p - \frac{1}{e}\nabla \cdot J_p. \qquad \ldots(5)$$

The terms G_n, G_p expressing the rate of generation of the electron-hold pairs involves the generation by heat Q_t, and by light $Q_x = \eta\alpha J(r)$, and the rate of the recombination $R_n = R_p = \gamma np$, and further $G_n = G_p = Q_t + \eta\alpha J(r)$, where :

e is the electron charge;

μ_n, μ_p are the electron mobility and the mobility of the hole respectively;

ϵ is the dielectric constant of the material;

D_n, D_p are the diffusion coefficients;

γ is the recombination coefficient;

η is the quantum efficiency; and

α is the coefficient of the optical absorption.

Without consideration of surface effect, if the following assumptions are fulfilled :

(1) $\partial n/\partial t,\ \partial P/\partial t = 0$, i.e. steady state;

(2) the sample is electrically insulated in space $J = J_n + J_p = 0$;

(3) the light excitation is weak and $n = n_0 + \Delta n$, $\Delta n \ll n_0$, $P = P_0 + \Delta P$, $\Delta P \ll P_0$;

(4) $P_0 = n_0$;

and (5) $Q_t - \gamma n_0 P_0 = 0$;

equations (1)–(5) are of the following form :

$$n_0(\mu_n + \mu_p) E + D_n \nabla \Delta n - D_p \nabla \Delta P = 0; \qquad \ldots(6)$$

$$J_n = c(\mu_n n_0 E + D_n \nabla \Delta n); \qquad \ldots(7)$$

$$\nabla \cdot E = \frac{e}{\epsilon} (\Delta P - \Delta n); \qquad \ldots(8)$$

and $$\alpha\eta J - \gamma n_0(\Delta n + \Delta P) + \frac{1}{e} \nabla \cdot J_n = 0. \qquad \ldots(9)$$

The solution of the system of equations (6)–(9) involving the increase of the concentration of the free electrons, yield the differential equation as follows :

$$- a_1 \Delta^2 \Delta n + a_2 \Delta \Delta n - a_0 \Delta n = b_2 \Delta J - b_0 J, \qquad \ldots(10)$$

where

$a_1 = \epsilon D_n D_p$,

$a_2 = n_0[D_p(e\mu_n + \epsilon\gamma) + D_n(e\mu_p + \gamma\epsilon)]$,

$a_0 = 2\gamma n_0 \sigma_0$,

$b_2 = \alpha\eta e D_p$,

$b_0 = \alpha\eta\sigma_0$

and $\sigma_0 = e n_0(\mu_n + \mu_p)$.

Since $D_n = (KT/e)\,\mu_n$, $D_p = (KT/e)\,\mu_p$, the coefficients are :—

(1) $a_1 = \dfrac{KT\mu_p}{e\gamma n_0}$. (2) $a_2 = \dfrac{\mu_p}{\mu_n} + \dfrac{2e\mu_p}{\gamma\epsilon} + 1$.

(3) $a_0 = \dfrac{2e^2 n_0(\mu_n + \mu_p)}{\epsilon KT\mu_n}$. (4) $b_2 = \dfrac{\alpha\eta\mu_p}{\gamma n_0 \mu_n}$.

(5) $b_0' = \dfrac{e^2(\mu_n + \mu_p)\alpha\eta}{\epsilon KT\mu_n\gamma}$

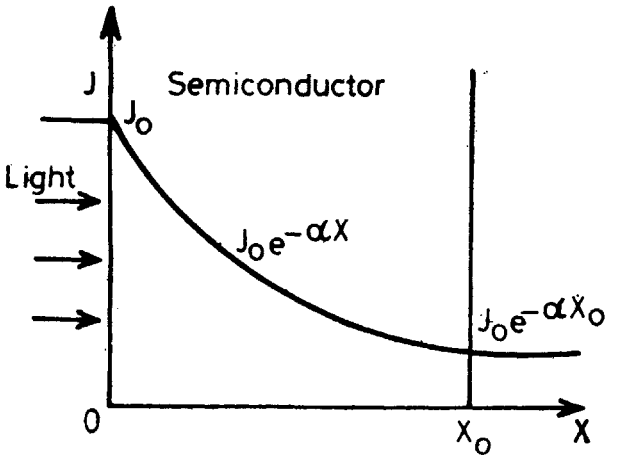

FIG 1 One dimensional case of a photoconduction film with the thickness of $x = 0$ and area $x = 0$ is illuminated.

If in the one-dimensional case a photoconductive film with the thickness of x_0 as shown in Fig. 1 is laid in the YZ plane and area $x = 0$ is illuminated, being $J(x) = J_0e^{-\alpha x}$, equation (10) is

$$a_4 \frac{d^4\Delta n}{dx^4} - a_2 \frac{d^2\Delta n}{dx^2} + a_0\Delta n = - bJ_0e^{-\alpha x}, \qquad ...(11)$$

where

$$b = \frac{\alpha\eta}{\gamma}\left(\frac{\mu_p\alpha^2}{\mu_n n_0} - \frac{e^2}{\epsilon KT}\cdot\frac{\mu_n + \mu_p}{\mu_n}\right).$$

By calculation of equation (11) and if $\alpha \neq S_i$, $(i = 1, 2, 3, 4)$, it is :

$$\Delta n(x) = \sum_{i=1}^{4} C_1e^{S_ix} \frac{bJ_0}{a_4\alpha^4 - a_2\alpha^2 + a_0} e^{-\alpha x}, \qquad ...(12)$$

where

$$S_i = \sqrt{\left[\frac{a_2 + \sqrt{(a_2^2 - 4a_0a_4)}}{2a_4}\right]} > 0, (i = 1, 2)$$

and

$$S_i = -\sqrt{\left[\frac{a_2 + \sqrt{(a_2^2 - 4a_0a_4)}}{2a_4}\right]} < 0, (i = 3, 4).$$

From the boundary conditions :

(1) $\lim_{x\to\infty} \Delta n(x) = 0$;

(2) $\Delta n(x) = \Delta P(x)$, for $x = 0$;

(3) $\left(\frac{dJ_n}{dx}\right)_{x=0} = 0$,

the coefficients $C_i (i = 1, 2, 3, 4)$ of the general solution of equation (12) are :

$$C_i = 0, \ (i = 1, 2);$$

$$C_3 = \frac{S_4^2}{S_3^2 - S_1^2}\left(\frac{\alpha\eta J_0}{2\gamma n_0} + \frac{bJ_0}{a_4\alpha^4 - a_2\alpha^2 + a_0}\right);$$

and

$$C_4 = \frac{S_3^2}{S_3^2 - S_4^2}\left(\frac{\alpha\eta J_0}{2\gamma n_0} + \frac{bJ_0}{a_4\alpha^4 - a_2\alpha^2 + a_0}\right).$$

The increase of the concentration of the free electrons along the x-axis caused by the illumination of an area of an infinitely large photoconductive plate, neglecting the influence of the surface domains is :

$$\Delta n(x) = \frac{1}{S_3^2 - S_4^2}\left(\frac{\alpha\eta}{2\gamma n_0} + \frac{b}{a_4\alpha^4 - a_2\alpha^2 + a_0}\right) \times (S_3^2 e^{S_4 x} - S_4^2 e^{S_3 x})\, J_0 \frac{b}{a_4\alpha^4 - a_2\alpha^2 + a_0} J_0 e^{-\alpha x}. \quad \ldots(13)$$

For photoconductive materials with immovable holes ($\mu_p = 0$) the coefficients a_i, $(i = 0, 2, 4)$; $b_i(0, 2)$ are $a_0 = 2\, e^2 n_0/\epsilon KT$, $a_2 = 1$, $a_1 = 0$, $b_0 = e^2\alpha\eta/\epsilon KT$, $b_2 = 0$ and following equations (14) and (15) we get the expressions

$$\Delta\, \Delta n - \frac{2e^2 n_0}{\epsilon KT}\, \Delta n = -\frac{e^2\alpha\eta}{\epsilon KT\gamma} J \quad \ldots(14)$$

or

$$\frac{d^2\Delta n}{dx^2} - \frac{2e^2 n_0}{\epsilon KT}\, \Delta n = -\frac{e^2\alpha\eta}{\epsilon KT\gamma} J_0 e^{-\alpha x} \quad \ldots(15)$$

respectively.

The solution for (15) with the boundary conditions

(1) $\lim_{x\to\infty} \Delta n(x) = 0$

and (2) $\Delta n(x) = \Delta P(n)$, for $x = 0$

is

$$\Delta n(x) = \frac{\alpha\eta J_0}{2\gamma n_0}\frac{1}{\alpha^2 - \lambda^2}(\alpha^2 e^{-\lambda x} - \lambda^2 e^{-\alpha x}), \quad \ldots(16)$$

if $\lambda^2 \neq \alpha^2$.

$$\Delta n(x) = \frac{\alpha\eta J_0}{2\gamma n_0}\left(1 + \frac{\lambda x}{2}\right) e^{-\lambda x}, \text{ if } \lambda^2 = \alpha^2, \quad \ldots(17)$$

where

$$\lambda^2 = \frac{2e^2 n_0}{\epsilon KT}$$

The increase of the film conductivity caused by the one-side illumination of the photoconductive film having just one kind of charge carriers (electrons) is :

$$\Delta\sigma(x) = e\mu_n \frac{\alpha\eta J_0}{2\gamma n_0}\frac{1}{\alpha^2 - \lambda^2}(\alpha^2 e^{-\lambda x} - \lambda^2 e^{-\alpha x}), \quad \ldots(18)$$

if $\alpha^2 \neq \lambda^2$.

$$\Delta\sigma(x) = e\mu_n \frac{\alpha\eta_i J_0}{2\gamma n_0} e^{-\alpha x}, \text{ if } \alpha^2 \ll \lambda^2. \qquad \ldots(19)$$

$$\Delta\sigma(x^3) = e\mu_n \frac{\alpha\eta_i J_0}{2\gamma n_0} e^{-\lambda x}, \text{ if } \alpha^2 \gg \lambda^2. \qquad \ldots(20)$$

$$\Delta\sigma(x) = e\mu_n \frac{\alpha\eta_i J_0}{2\gamma n_0} \left(1 + \frac{\lambda x}{2}\right) e^{-\lambda x}, \text{ if } \alpha = \lambda. \qquad \ldots(21)$$

In the case of $\alpha^2 \ll \lambda^2$ the light penetrates deeply into the film and the non-uniform change of the conductivity is caused by the optical excitation of the carriers in the whole film. For $\alpha^2 \gg \lambda^2$, the light is absorbed even in a small depth under the surface and the change of the conductivity is caused by the electrons which diffuse from the surface in to the depth of the film.

If the one-side illuminated plate of the photoconductive material creates the dielectric of the plate capacitor with the electrodes on the areas $x = 0$, and $x = x_0$, and if a small harmonic voltage is applied on them, then

$$U = U_0 e^{i\omega t}, \frac{U_0}{x_0} \ll 2\frac{KT}{eL_D},$$

where L_D is the Debye length, then the impedance of the length element dx of a unit area is (Fig. 2) :

$$dZ = \frac{dx}{\sigma(x) + i\omega\epsilon};$$

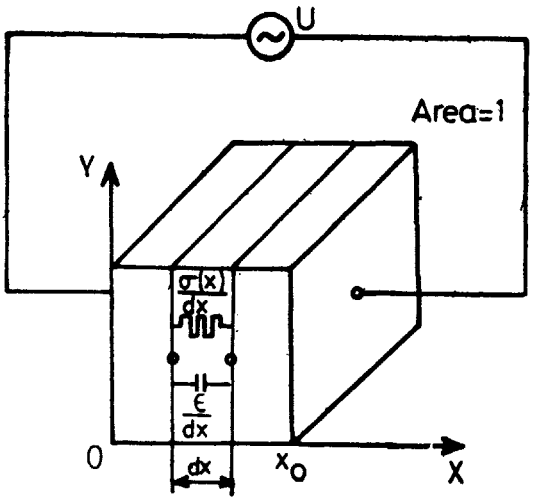

FIG 2 One side illuminated plate of the photoconductive material creates the dielectric of the plate capacitor with the electrodes on the areas $x = 0, x = x_0$. V is a small harmonic voltage and dx = length element dx of a unit area.

and the admittance of the whole capacitor with the film thickness x_0 is

$$Y = G + iwC = \left[\int_0^{x^0} \frac{dx}{\sigma(x) + iw\epsilon} \right]^{-1}$$

$$= \frac{A}{A^2 + (w\epsilon B)^2} + iw\epsilon \frac{B}{A^2 + (w\epsilon B)^2},$$

where

$$B = \int_0^{x^0} \frac{dx}{d^2(x) + w^2\epsilon^2}, \qquad \ldots(22)$$

and

$$A = \int_0^{x^0} \frac{\sigma(x)}{\sigma^2(x) + w^2\epsilon^2}\, dx$$

$$= \sigma_0 B + \int_0^{x^0} \frac{\Delta\sigma(x)}{\sigma^2(x) + w^2\epsilon^2}\, dx. \qquad \ldots(23)$$

By substitution of equations (19) and (20) into (22) and (23) and by considering $\Delta\sigma(x) \ll \sigma_0$, the conductivity and the capacity of the photocapacitor are:

$$G = \frac{\sigma_0}{x_0}\left[1 + \left(1 + \frac{w^2\epsilon^2}{\sigma_0^2} \right) \frac{\frac{1}{2a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma k_1 J_0}{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 \exp(-a_1) J_0}}{1 - \frac{1}{a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 J_0}{\sigma_0^2 + w^2\epsilon^2\, 2\sigma_0 k_1 \exp(-a_1) J_0}} \right]; \qquad \ldots(24)$$

and

$$C = \frac{\epsilon}{x_0}\left[1 - \frac{1}{a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 J}{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 \exp(-a_1) J_0} \right], \qquad \ldots(25)$$

where

$$a_1 = \begin{cases} \alpha x_0, \text{ for } \alpha^2 \ll \lambda^2. \\ \lambda x_0, \text{ for } \alpha^2 \gg \lambda^2. \end{cases} \qquad \ldots(26)$$

and

$$k_1 = e\mu_n \frac{\alpha\eta}{2\gamma n_0}.$$

The conductivity and the capacity of the capacitor without illumination is calculated from equations (24) and/or (25) respectively for $J_0 = 0$.

$$G_0 = \frac{\sigma_0}{x_0}, \quad C_0 = \frac{\epsilon}{x_0}.$$

These equations correspond to the conductivity and capacity of a capacitor calculated from the geometric dimensions : the area of electrodes and the thickness of the dielectric x_0.

The relative changes of G and C caused by the illumination are:

$$\frac{\Delta G}{G_0} = \left(1 + \frac{w^2\epsilon^2}{\sigma_0^2}\right) \frac{\frac{1}{2a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 J_0}{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 \exp(-a_1) J_0}}{1 - \frac{1}{a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 J_0}{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 \exp(-a_1) J_0}} \quad \ldots(27)$$

and

$$\frac{\Delta C}{C_0} = \frac{\frac{1}{a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 J_0}{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 \exp(-a_1) J_0}}{1 - \frac{1}{a_1} \ln \frac{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 J_0}{\sigma_0^2 + w^2\epsilon^2 + 2\sigma_0 k_1 \exp(-a_1) J_0}} \quad \ldots(28)$$

by simplification for $a_1 \gg 1$.

$$\frac{\Delta G}{G_0} = \frac{\nu}{2a_1} \ln\left(1 + \frac{2k_1}{\nu\sigma_0} J_0\right). \quad \ldots(29)$$

$$\frac{\Delta C}{G_0} = \frac{1}{a_1} \ln\left(1 + \frac{2k_1}{\nu\sigma_0} J_0\right), \quad \ldots(30)$$

where

$$\nu = 1 + \left(\frac{w\epsilon}{\sigma_0}\right)^2.$$

Experimental Procedures

CdTe thin films were prepared by evaporation of CdTe under a vacuum of 3×10^{-5} mm Hg. They were evaporated onto glass substrates, at 100 °C, provided with indium electrodes. The dimensions of each thin film prepared are of 0.3cm² area and 0.1 μ_m thickness. The components used were of pure analytical grade (99.97 per cent).

Electrical Measurement

The capacitance and dielectric loss (tan δ) CdTe thin films was measured using Universal Measuring Bridge type B 151 (England). For all samples adopted in this way, the change of capacitance was recorded due to change of illumination intensity by varying the distance from Hg light of wavelength 365nm.

Results and Discussion

The relative change of the photocapacitor capacity *vs* apart distance from Hg light source is plotted in Fig. (3). The capacity change yields 5 per cent for separated distance 2cm at 1kHz. The change of capacitance decreases with increasing the apart distance.

The ratio ϵ/σ_0 obtained direct by measuring the capacity and conductivity of the sample is

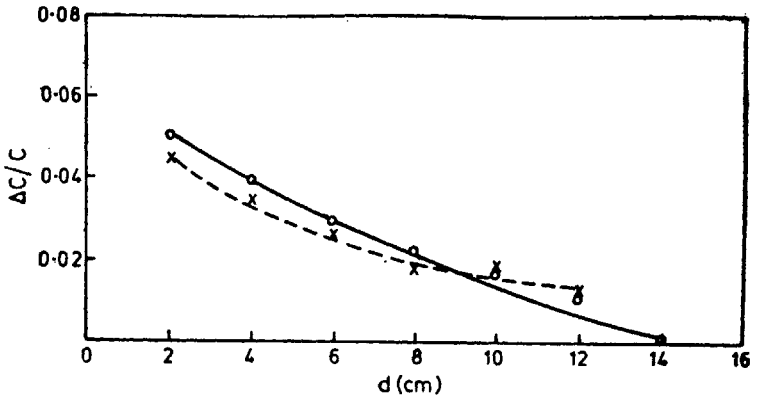

FIG 3 The dependence of the relative capacity change on the distance between mercury light and the thin film of CdTe, ○ the experimental results; x theoretical model.

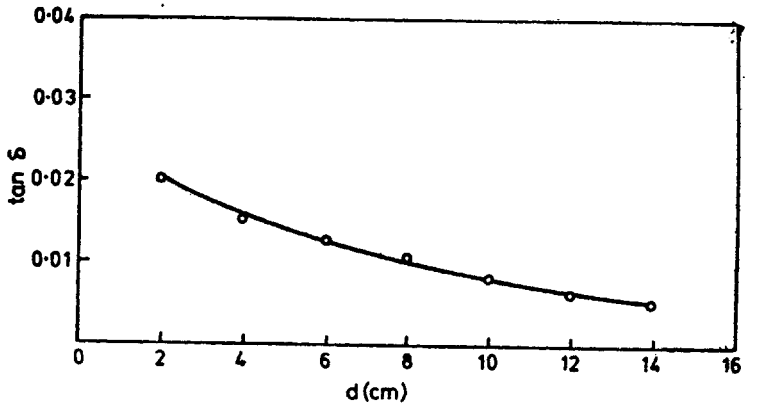

FIG 4 Effect of the apart distance on the dielectric loss of CdTe thin film.

$$\left(\frac{\epsilon}{\sigma_0}\right)_{\text{exp.}} = 9 \times 10^{-4}\, F\Omega^{-1}$$

and using equation (30), good fitting between the experimental and theoretical results as shown in Fig. (3).

Photo-dielectric Loss

The dielectric loss of the dark and illuminated sample is measured as a function of the apart distance (Fig. 4). Samples of p-type CdTe were subjected to illumination and the change of conductivity it was ascertained that an increase in acceptor concentration occurs on the level with activation energy 0.3 eV.[5] The concentration of acceptors increases on decreasing the distance due to migration of the dislocations produced give rise to V^{Cd} and/or V^{Te} (both types simultaneously).

V^{Cd} acts as an acceptor and V^{Te} as a donor. These vacancies gave rise for dielectric loss.

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