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CdTe HOLE LIFETIME FROM THE GAMMA-RAY AND PHOTO-INDUCED EFFECTS

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Abstract: Two independent methods, the gamma-ray induced photovoltaic effect and the monochromatic light induced photoeffect, were used for determination of the minority carrier lifetime in indium doped n-type CdTe. The existing expressions for collection efficiency of electron-hole pairs generated by visible light near the p-n junction were extended to include a contribution of the depletion layer. P-n junctions formed by electroless plating of gold had a relatively high capacitance associated with a very narrow depletion region. The short-circuit current of the diodes was measured during irradiation in the Co^{60} gamma source. The values of lifetime of holes in CdTe (of the order of $5 \cdot 10^{-10}$ s), obtained by the two methods, were in agreement within the limits of experimental errors.

1. Introduction

It is well known that at the present level of semiconductor technology the growth of high quality single crystals, except in the case of Si and Ge, is far from being satisfactory. Beside influencing some other physical properties, the presence of a large number of various kinds of defects in the crystalline lattice has an important consequence, a large reduction in the lifetime of minority charge carriers. If the magnitude of this quantity is less than about 1 μs then, the standard methods for lifetime determination, based on carrier injection or decay, are inapplicable. Such a situation exists in the case of CdTe, a semiconducting compound interesting from the standpoint of device application. To be able to determine the value of minority carrier lifetime with sufficient accuracy and trying to increase it is the main task before many useful devices made from the semiconducting compounds can be produced.

The aim of this paper is to present the results of determination of the minority carrier lifetime in n-type CdTe by the two independent methods based on the existence of a p-n junction. To our knowledge, the first of them connected with gamma-ray induced photocurrent has not been applied to CdTe up to now, and for the second, based on the photovoltaic effect, more general expressions have been derived than those used in a similar work[1]. Several other methods such as pulse height response to α particles[2, 3], or analysis of a reverse dark current of the junction[4] have been also employed previously. The highest values for τ in CdTe so far reported for relatively pure high resistivity materials were of the order of 10^{-8} s.

2. *Gamma-ray induced photovoltaic effect*

If the p-n junction is situated close to the one electrode, and the other electrode is more than a couple of diffusion lengths away, the short-circuit current per unit area i_{sc} is equal to

$$i_{sc} = e\, g\, L_p\,, \tag{1}$$

where e is electronic charge, g generation rate and L_p diffusion length of minority carriers.

Here we have supposed that the thickness of a *p*-region is much smaller than the diffusion length L_n of the electrons so that the short-circuit current through the junction is supported essentially only by the carriers generated within the hole diffusion length in the *n*-region.

If the generation rate g is constant within the volume of the diode, as it is true for the weakly absorbed gamma irradiation, by measuring i_{sc} generated by the exposure of the p-n junction to the Co^{60}-gamma source it is possible to determine the minority carrier diffusion length L_p, and with equation (2)

$$L_p = \sqrt{D_p \tau_p} \tag{2}$$

the minority carrier lifetime τ_p. Here, diffusion coefficient D_p should be determined by an independent method, usually by use of Einstein's relation

$$D_p = \mu_p \frac{k\,T}{e}\,, \tag{3}$$

where μ_p is the hole mobility, k Boltzmann's constant, and T the absolute temperature.

The generation rate g is given by

$$g = N_{\gamma}\, \varkappa \frac{E_c}{\varepsilon}\,, \tag{4}$$

where N_γ is the gamma flux per unit area, $\varkappa$ the total absorption coefficient of γ-rays, E_c is the average energy of a Compton electron, and ε the average energy required to produce one electron-hole pair.

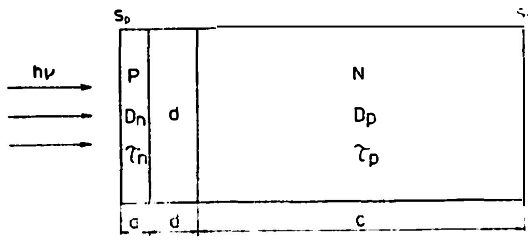

Fig. 1 — Model of a p-n junction.

By using Equ. (4) it is important to realize experimental conditions so that the Compton electrons, which are a dominant result of the gamma-ray interaction with matter in the 1 MeV energy region, loose completely their energy within the diffusion length from the junction. In spite of the fact that their range is of the order of 1 mm, i. e. usually much greater than L_p, the above condition can be still fulfilled by surrounding the p-n junction by an absorbing material, so that the same number of electrons enters the active region as leaves it.

3. Collection efficiency of electron-hole pairs generated by visible light

Collection efficiency K of electron-hole pairs created in the vicinty of a p-n junction in a photovoltaic regime is defined as

$$K = \frac{i_c}{I_0}, \tag{5}$$

where i_c is the short-circuit current density obtained experimentally and I_0 the maximal theoretical value under assumption that every photon absorbed creates an electron-hole pair which contributes to the short- circuit current.

By solving equation of continuity under the appropriate boundary conditions for a p-n junction with homogeneously distributed dopants (Fig. 1), if the light falls perpendicularly on the p-side of the junction of the thickness a, the depletion region of the thickness d, and n-type region of the thickness c, the collection efficiencies for those regions are given by[5]

$$K_p = \frac{(\alpha L_n)^2}{(\alpha L_n)^2 - 1}\left[\frac{1 + \dfrac{P_n}{\alpha L_n}}{\operatorname{ch}\dfrac{a}{L_n} + P_n \operatorname{sh}\dfrac{a}{L_n}} - \left(1 + \frac{1}{\alpha L_n}\,\frac{P_n \operatorname{ch}\dfrac{a}{L_n} + \operatorname{sh}\dfrac{a}{L_n}}{\operatorname{ch}\dfrac{a}{L_n} + P_n \operatorname{sh}\dfrac{a}{L_n}}\right) e^{-\alpha a}\right]. \tag{6}$$

$$K_d = 2\,\mathrm{sh}\,\frac{\alpha d}{2}\,\mathrm{e}^{-\alpha\left(\frac{d}{2}+a\right)}, \tag{7}$$

$$K_N = \frac{(\alpha L_p)^2}{(\alpha L_p)^2 - 1}\left[\left(1 - \frac{1}{\alpha L_p}\,\frac{P_p\,\mathrm{ch}\frac{c}{L_p} + \mathrm{sh}\frac{c}{L_p}}{\mathrm{ch}\frac{c}{L_p} + P_p\,\mathrm{sh}\frac{c}{L_p}}\right)\mathrm{e}^{-\alpha(a+d)} - \right.$$
$$\left. - \frac{1 - \frac{P_p}{\alpha L_p}}{\mathrm{ch}\frac{c}{L_p} + P_p\,\mathrm{sh}\frac{c}{L_p}}\,\mathrm{e}^{-\alpha(c+d+a)}\right], \tag{8}$$

where $P_p = s_p L_p/D_p$ and $P_n = s_n L_n/D_n$.
$L's$ and $D's$ are connected by equation (2), s_n, s_p are the electron and hole surface recombination velocities, respectevely, and α absorption coefficient.

For a very small a, i. e. for the surface p-type layer of a thickness much smaller than the diffusion length L_n, except in the case of extremely high surface recombination velocities, it is justified to take as an approximation

$$K_P \approx 0. \tag{9}$$

Furthemore, as $\mathrm{e}^{-a\alpha} \to 1$ equation (7) reduces to

$$K_d = 1 - \mathrm{e}^{\alpha d} \tag{10}$$

We see that for d not too large (say of the order of 0.2 μ), K_d is small, and the major contribution to the experimentally measured collection efficiency K comes from the collection of charge carriers generated in the n-region.

In the case of CdTe absorption coefficient α in the region of interest (0.5 — 0.8 μ) is a strong function of the wavelength λ of the incident light[6].

If we choose such a λ that $\alpha(d + c) \gg 1$, the second term on the right side of equation (8) vanishes, and as usually $c \gg L_p$ and therefore $\mathrm{ch}\frac{c}{L_p} \approx \frac{c}{L_p}$, equation (8) takes a simplified form

$$K_N = \frac{\alpha L_p}{\alpha L_p + 1}\,\mathrm{e}^{\alpha d}. \tag{11}$$

As in our case

$$K = K_N + K_d = \frac{\alpha L_p + 1 - \mathrm{e}^{-\alpha d}}{\alpha L_p + 1}, \tag{12}$$

and the minority carrier diffusion length is given by

$$L_p = \frac{K - (1 - e^{-d/\delta})}{1 - K}\,\delta\,, \tag{13}$$

where the absorption depth $\delta = 1/\alpha$.

Equ. (13) by neglecting the collection in the space charge region of the thickness d reduces to the one used in the previous work[1].

4. *Experimental*

As a starting material we used p-type single crystal CdTe with resistivity about 1000 Ω cm obtained by the zone-levelling method. In order to produce an n-type material, indium was evaporated on one side of the wafer thus insuring conditions for diffusion from an infinite source. Diffusion of In in CdTe was carried out in a closed evacuated quartz tube placed in a 3-zone furnace. Actually, two zones were used, one with the wafers at 850 °C, and the necessary pressure in the system was maintained by the mixture of elemental In and Cd in the atomic ratio 1 : 2, placed in the second zone at 800 °C.

Diffusion coefficient of In in CdTe was found to be[7]

$$D = 4.1 \cdot 10^{-2} \exp\left(-\frac{1.6 \text{ eV}}{kT}\right), \tag{14}$$

which gives $D = 2.8 \cdot 10^{-9}$ cm^2 s^{-1} at $T = 1123$ °K (850 °C).

In the case of diffusion from the infinite source, the profile of the dopant concentration is given by

$$N(x, t) = \frac{N_0}{2}\left(1 - \operatorname{erf}\frac{x}{2\sqrt{Dt}}\right), \tag{15}$$

where N_0 is the dopant surface concentration, and t is the diffusion time.

For $t = 1$ hr and $N(x)/N_0 = 0.1$ we found from equation (15) the diffusion depth of In $x = 0.058$ mm.

As the thickness of the wafers was of the order of 1 mm, an n-p junction was formed by the diffusion. This fact enabled us to determine the dopant concentration profile by lapping and 4-point sheet resistivity measurements. Initially, the indium evaporated side of the wafer had $\rho' = 0.07$ Ω cm, and the opposite side $\rho'' = 0.6$ Ω cm. By removing the layer 220 μ thick, a thermoelectric p-n probe showed p-type conductivity. Then, the complete p-type region was removed by lapping until the second, backside n-type region was reached, unhomogeneously doped with In (about 200 μ thick).

Efficient photodiodes were formed by electroless plating of gold on the lower doped side of the slice by $AuCl_3$ solution. It seams that according to Cusano's data[1] a p-type layer and heterojunction was formed. As an ohmic back contact a piece of indium was alloyed. The diode was imbedded in an

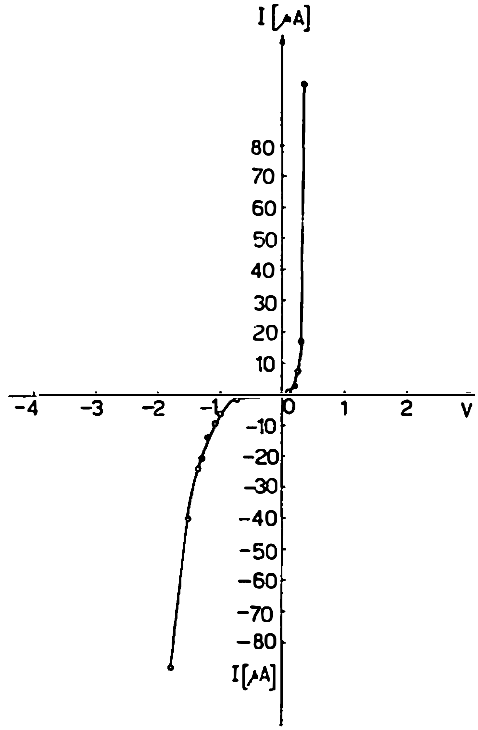

Fig. 2 — I—V characteristics of the diode INZ-1 at room temperature.

insulating plastic material of high resistivity (10^{14} Ω cm), and mounted in a coaxial housing. The front contact was finally made by a gold evaporation.

In order to get some basic data on the properties of the p-n junction, the I—V and capacitance measurements were performed. The later were done using the Marconi 0.1 % Universal bridge with an external low amplitude signal and the General Radio tuned amplifier and null detector.

Spectral response of the junction to the monochromatic light was measured by a glass-prism monochromator, and the light flux falling on the diode was determined by a calibrated E. G. and G. silicon photodiode.

The thickness of the front gold electrode was obtained by resistivity measurements using a Thomson bridge.

One of the diodes was irradiated in the Co^{60} gamma-ray source in a flux of $1.7 \cdot 10^{11}$ photons $cm^{-2} s^{-1}$ up to the total time-integrated fluence of $1.2 \cdot 10^{16}$ photons cm^{-2}. An aluminium spacer 0.5 mm thick was placed close to the p-n junction in order to satisfy conditions imposed by equation (4). The short-circuit current of the diode was also measured during irradiation.

5. *Results and discussion*

The I—V characteristics at room temperature of one of the diodes is given in Fig. 2. It has a pronounced »knee« and an internal resistance of several hundreds of kohms for low bias. As the capacitance data revealed, a relatively low breakdown voltage is associated with the existence of a very narrow depletion region, and therefore, with the high electric field (greater than $7 \cdot 10^4$ V/cm) in the junction region. Namely, the diode of the surface area of only 3 mm^2 had the measured capacitance of the order of 1500 pF. For the purpose of an estimate, if we use the expression for the capacitance of the plate condenser what is surely an oversimplification of the real situation and taking the appropriate value for the dielectric constant for CdTe ($\varepsilon_0 = 10.6$), the thickness of the depletion region should be about 0.2 μ.

Fig. 3 shows the reciprocal square value of the short-circuit current as a function of the gamma-ray fluence of a diode of the area of 1 mm^2. The theory predicts a linear or a sublinear dependence. At the beginning of irradiation there is even an increase in the short-circuit current associated with surface effects. With the increase of the gamma fluence the lifetime of minority carriers which is proportional to i_{sc}^2 decreases. It is a very sensitive parameter which reflects even small changes in the concentration of recombination centres due to the introduction of radiation defects.

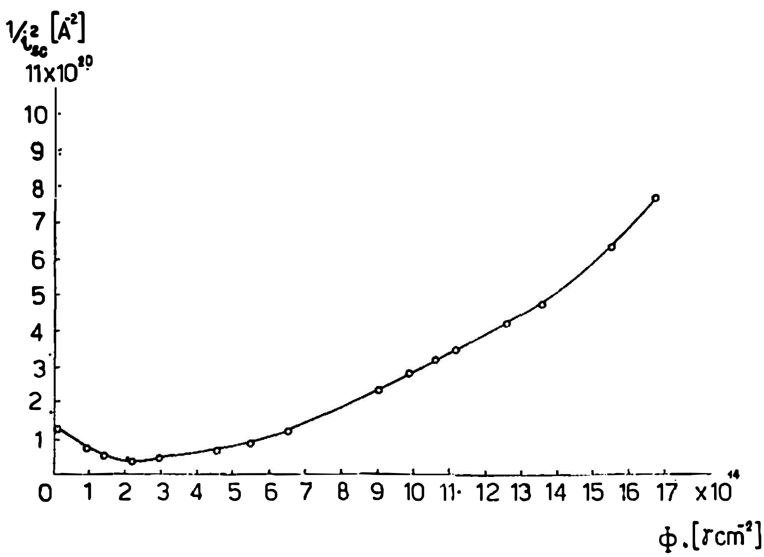

Fig. 3 — The reciprocal square value of the short-circuit current as a function of the gamma-ray fluence of the diode INZ-2.

For determination of lifetime of holes in n-type CdTe, it is sufficient to use the initial value of the gamma-ray induced short-circuit current of still undamaged material which was equal to $8.8 \cdot 10^{-11}$ A.

By putting numerical values, $N_\gamma = 1.7 \cdot 10^{11}$ $cm^{-2} s^{-1}$, $K = 0.15$ cm^{-1}[8], $E_c = 0.59$ MeV, and $\varepsilon = 4.9$ eV [3] in Equs. (4) and (1), the diffusion length $L_p = 0.18$ μ was obtained.

As mobility of holes (μ_p) in the p-type CdTe was found to be about 80 $cm^2 V^{-1} s^{-1}$ at room temperature[9], Equs. (3) and (2) gave for the lifetime of minority carriers $\tau_p = 1.6 \cdot 10^{-10}$ s. This value should be considered as a lower limit for the hole lifetine in our n-type CdTe material, since the conditions of 100% efficiency of the Compton electrons, as discussed in the second paragraph, were only partially fulfilled in our experiment.

The spectral dependence of the photovoltaic effect, shown in Fig. 4, was used in the second method for the lifetime determination. For the calculations, a value of the short-circuit current density i_c at 0.7 μ was taken. This wavelength was chosen in order to satisfy conditions under which Equ. (13) had been derived, and to insure that the photocarriers were created predominantly in the n-type region.

The flux density of the monochromatic light was measured to be equal to $1.74 \cdot 10^{14}$ photons $cm^{-2} s^{-1}$. In order to obtain I_0 in Equ. (5), this value was

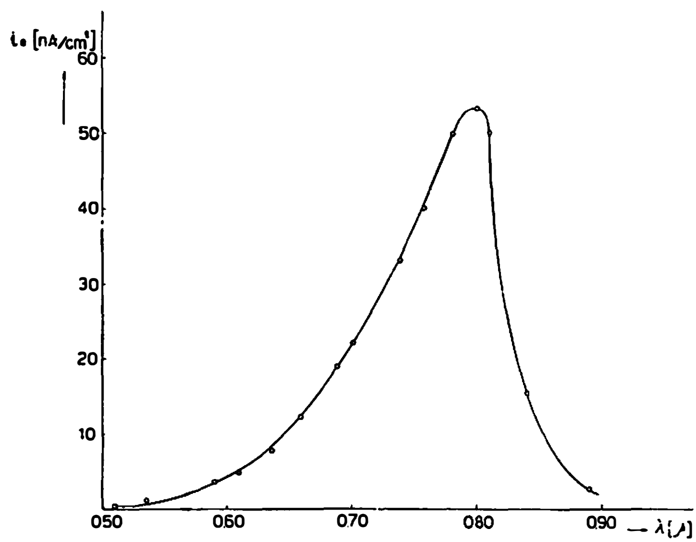

Fig. 4 — The spectral dependence of the short-circuit current generated by light.

corrected taking into account only transmitted flux through the surface gold layer. The thickness of the layer was determined to be about 900 Å from electrical measurements, taking the appropriate value of resistivity of gold films[10].

By knowing the film thickness, transmission coefficient of gold thin films was found to be 0.26%[11] for the wavelength of interes. Therefore, collection efficiency turned out to be $K = 22.6$ [nA/cm²]/60 [nA/cm²] = 38%.

Substituting appropriate values ($\alpha = 10^4 \, cm^{-1}$, $d = 0.2 \, \mu$) in Equ. (10), the contribution of the depletion layer to the collection efficiency comes out $K_d = 0.18$.

As $\delta = 1 \, \mu$, equation (13) gives for the hole diffusion length $L_p = 0.32 \, \mu$, a value somewhat greater than that found by the first method.

Using Equs. (2) and (3) and taking the same numerical values as before, we get $\tau_p = 5 \cdot 10^{-10}$ s. Taking into account some possible sources of errors, such as uncertainity in gold thickness determination, in absorption coefficient at the given wavelength and in hole mobility, we estimate that this value be correct within a factor of 2. Its magnitude is comparable to the values usually found in lower resistivity n-type CdTe single crystals[1)], but suggests also the presence of a higher number of lattice defects in such a material.

Further studies on some photoelectronic properties of our p-n junctions in CdTe with a special impurity distribution were also undertaken, and results will be published in a separate publication.

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ODREĐIVANJE VREMENA ŽIVOTA ŠUPLJINA U CdTe POMOĆU EFEKATA INDUCIRANIH GAMA ZRAKA I FOTONIMA SVJETLOSTI

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Sadržaj

Za određivanje vremena života manjinskih nosilaca naboja u n-tipu CdTe dopiranom indijem korištene su dvije neovisne metode. Jedna se zasniva na mjerenju struje kratkog spoja izazvane djelovanjem gama zračenja u kobaltnom izvoru, a druga na fotovoltaičnom efektu uslijed fluksa monokro-

matskog svjetlosnog zračenja. Obje metode pretpostavljaju postojanje p-n prijelaza, koji je ostvaren nanošenjem zlatnog filma iz otopine na uzorke n-tip kadmijevog telurida.

Postojeći teoretski izrazi za efikasnost sakupljanja fotogeneriranih nosilaca naboja prošireni su uzimajući u obzir i doprinos iz područja iscrpljenja. Ustanovljen je relativno velik kapacitet dioda, koji je pripisan vrlo uskom području iscrpljenja. Za vrijeme ozračavanja u kobaltnom izvoru mjerena je struja kratkog spoja u ovisnosti o primljenoj dozi. Vrijednosti za vrijeme života šupljina u CdTe (oko $5 \cdot 10^{-10}$ s) dobivene dvjema metodama slažu se unutar eksperimentalnih pogrešaka.