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X-ray CdZnTe detector in transverse and longitudinal photoconductivity mode

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The work considers „transverse“ and „longitudinal“ photoconductivity modes, regarding the direction of radiation, photoconductivity in semiconductor detectors of CdZnTe. Mathematical calculations were made from the representation of the internal area of the detector in the form of radiation absorption sites. The results of the calculations are compared with experimentally measured photocurrent of the detector with a cross section of 2×2 mm CdZnTe from the direction of its radiation by X-ray. From the ratio of photocurrents in the range of X-ray radiation energies 35–72 keV for these two cases, a linear coefficient of X-ray absorption by the CdZnTe detector is determined.

Keywords: CdZnTe detector, efficient energy, X-ray radiation, resistance, photocurrent, photoconductivity.

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Introduction

The photoconductivity of semiconductors is used successfully to construct X-ray radiation detectors. CdZnTe crystals are a promising material for detectors operating in the hard X-ray range (above 35 keV). The region of absorption of the photon energy in a CdZnTe detector is located between the contacts, which are used to apply external voltage (50 V or higher), and is specified by the size of the crystal. It was noted that the sensitivity of a CdZnTe detector in the effective energy interval of 28–72 keV with the X-rays directed perpendicular to the applied electric field is 1.5 times higher than the sensitivity measured with the X-rays parallel to the electric field [1,2]. The modes of „transverse“ and „longitudinal“ photoconductivity in semiconductor tomographic detectors based on CdTe have already been discussed [3]. The difference in photoconductivity was attributed to the parallel and series connection of an irradiated region of the crystal and a scarcely irradiated one with a higher resistance; however, these explanations were not substantiated with mathematical calculations.

The aim of the present study is to examine the cases of „transverse“ and „longitudinal“ photoconductivity in semiconductor detectors and to compare calculated data with the experimentally measured photocurrents of a CdZnTe detector corresponding to different directions of X-ray irradiation.

1. Examination of detector operation

Let us consider an isotropic detector crystal in the shape of a rectangular parallelepiped with its sides having the lengths of M, L, and D along axes X, Y, and Z, respectively (see figure). When bias voltage V is applied along axis Y, the current of free carriers with density N is produced. In the general case, this density is defined as

$$N = N_{X\text{-}ray} + N_{dark}, \quad (1)$$

where $N_{X\text{-}ray}$ is the density of carriers produced due to absorption of X-ray quanta and N_{dark} is the number of free carriers producing „dark“ current without irradiation. Under normal operation, the contribution of the latter carriers is insignificant, and the „dark“ current, which has an intensity of $\sim 10^{-9}$–10^{-8} A, may be neglected in calculations. With weak attenuation of radiation over the propagation length in the crystal, the diffusion current may also be neglected.

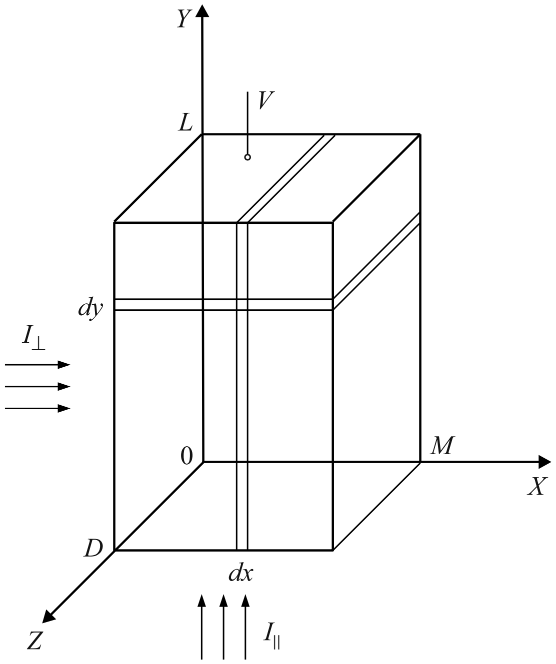
In the case of „transverse“ irradiation (i.e., when the crystal is irradiated in the X direction), we present the sample as a parallel connection of conducting layers with thickness dx (see figure). The photocurrent in this region of the crystal is

$$dJ_{\perp} = j_x \cdot D \cdot dx, \quad (2)$$

where (with the diffusion current taken into account, see Appendix) [4]:

$$j_x = q \cdot \mu_n \cdot N_x \cdot E, \quad (3)$$

where μ_n is the mobility of carriers with charge q and E is the electric-field intensity produced by applying electric voltage V. Neglecting the distortion of the electric-field intensity due to the diffusion current and neglecting the presence of „dead layers“ below the metallic contact (less than 1 μm) of the detector electrode, we assume that $E = V/L$. Under the influence of radiation, a corresponding number of carriers are produced in a semiconductor crystal.



Detector crystal in the shape of a parallelepiped under X-ray irradiation that is transverse ($I_\perp$) and longitudinal ($I_\parallel$) with respect to applied voltage V.

The carrier density varies due to X-ray radiation attenuation in accordance with the following law [5]:

$$N_x = N_0 \cdot \exp(-\mu \cdot x), \tag{4}$$

where μ is the linear coefficient of radiation absorption by matter, which generally depends on energy, and N_0 is the carrier density near the irradiated crystal face.

The photocurrent of the entire crystal sample is obtained by inserting (3), (4) into (2) and integrating (2) with respect to dx from 0 to M:

$$J_\perp = (q \cdot \mu_n \cdot N_0 \cdot E \cdot D/\mu) \cdot [1 - \exp(-\mu \cdot M)]. \tag{5}$$

The overall resistance of the sample is

$$R_\perp = V/J_\perp = \mu \cdot (q \cdot \mu_n \cdot N_0 \cdot L \cdot D)^{-1} \times [1 - \exp(-\mu \cdot M)]^{-1}. \tag{6}$$

In order to examine the conditions of current passage under irradiation in the Y direction („longitudinal“ case), we present the sample as a series connection of conducting layers of thickness dy with conductivity $\sigma = j/E$. The electric resistance of a single layer is

$$dR_\parallel = dy/(\sigma \cdot M \cdot D) = E \cdot dy/(j_y \cdot M \cdot D), \tag{7}$$

with current density

$$j_y = q \cdot \mu_n \cdot N_y \cdot E, \tag{8}$$

where the carrier density varies due to X-ray radiation attenuation in accordance with the following law:

$$N_y = N_1 \cdot \exp(-\mu \cdot y). \tag{9}$$

The overall resistance of the sample is obtained by inserting (9), (8) into (7) and integrating (7) with respect to dy from 0 to L:

$$R_\parallel = (q \cdot \mu_n \cdot N_1 \cdot M \cdot D \cdot \mu)^{-1} \cdot [\exp(\mu \cdot L) - 1]. \tag{10}$$

The following relation may be derived from Eqs. (6) and (10):

$$R_\parallel/R_\perp = (N_0/N_1) \cdot (L \cdot M \cdot \mu \cdot \mu)^{-1} \cdot [\exp(\mu \cdot L) - 1] \times [1 - \exp(-\mu \cdot M)]. \tag{11}$$

The values of N_0 and N_1 are directly proportional to the intensities of incident X-ray radiation at different incidence directions. Assuming that the intensities are equal ($N_0 = N_1$) and the cross section of the detector crystal is square in shape ($L = M$), we find

$$R_\parallel/R_\perp = (L \cdot \mu)^{-2} \cdot [\exp(\mu \cdot L) - 1] \cdot [1 - \exp(-\mu \cdot L)]. \tag{12}$$

Within the approximation of weak radiation attenuation $\mu \cdot L \ll 1$, we find approximation $\exp(\pm\mu \cdot L) \approx \approx 1 \pm \mu \cdot L/1! + (\mu \cdot L)^2/2! \pm (\mu \cdot L)^3/3! + \ldots$ and, having inserted this result into (11), obtain the following

$$R_\parallel/R_\perp \approx 1 + (\mu \cdot L)^2/12. \tag{13}$$

It follows from relation (13) that the photocurrent of a detector under irradiation in the case of „transverse“ photoconductivity is higher than in the case of „longitudinal“photoconductivity. In addition, the measurement of the $R_\parallel/R_\perp$ ratio allows one to estimate the coefficient of radiation attenuation within the detector.

The data from [1] were used as the experimental values. The n-type $Cd_{0.9}Zn_{0.1}Te$ single crystal used in measurements was grown at the Shubnikov Institute of Crystallography of the Russian Academy of Sciences. A radiation source with a W anode was used. The tube anode voltage was 100 kV, and the anode current was 0.1 mA. Ohmic contacts for detectors were fabricated by chemical deposition of Au from an aqueous solution of $AuCl_3$. The measurement results are presented in the table. The effective energies of X-ray radiation are given in the first row: 35, 61, and 72 keV. The effective radiation energy was set by a target of copper filters with different thickness (0.1, 0.8, and 1.6 mm [6]). The ratio of sensitivities of a CdZnTe detector with a cross section of 2×2 mm in „transverse“ and „longitudinal“ photoconductivity modes, which corresponds directly to formula (12), is given in the second row. The third row contains the values of $\mu \cdot L$ calculated using (12). The corresponding linear coefficients of radiation absorption by matter (μ) are given in the fourth row.

Within the considered approximation, formula (12) yields fairly accurate results at effective X-ray energies above 35 keV. Thus, if the ratio of detector photocurrents in „transverse“ and „longitudinal“ photoconductivity modes is known, one may determine the effective X-ray radiation

Dependence of linear coefficient of radiation absorption μ on the ratio of photocurrents in „transverse" and „longitudinal" photoconductivity modes

Effective energy, keV	35	61	72
Ratio of photocurrents in „transverse" and „longitudinal" photoconductivity modes	1.7–2	1.36	1.24
$\mu \cdot L$	2.4–3	2	1.6
μ, cm^{-1}	12–15	10	8

energy based on the value of μ. With the examined photodetector design, the radiation energy may be determined accurately below 100 keV. If a detector with a cross section larger than 2×2 mm is used, the upper limit of accurate determination of the effective radiation energy may be extended beyond 100 keV. At higher energies, when μ assumes a relatively low value, the ratio of „transverse" and „longitudinal" photoconductivities in formula (13) tends to unity.

Conclusion

The „transverse" and „longitudinal" photoconductivity modes in CdZnTe semiconductor detectors were examined. The results of calculation of the ratio of „transverse" and „longitudinal" photoconductivities are compared with the experimentally measured photocurrents of a CdZnTe detector under X-ray irradiation at different incidence directions. The ratio of photocurrents allows one to determine the linear coefficient of radiation absorption by matter in the 35–100 keV X-ray energy range and the effective energy.

Appendix

The total carrier (electron) current is a combination of drift and diffusion currents [4]:

$$j_x = j_{drift} + j_{diff} = q \cdot \mu_n \cdot N_x \cdot E + q \cdot \mu_n \cdot (k \cdot T/q) \times dN_x/dx, \quad \text{(A1)}$$

where $k \cdot T/q$ is the thermal potential, which is equal to 0.026 V at room temperature. Inserting (4) into (A1), we obtain

$$j_x = q \cdot \mu_n \cdot N_0 \cdot \exp(-\mu \cdot x) \cdot [E - \mu \cdot (k \cdot T/q)]. \quad \text{(A2)}$$

The diffusion current is neglected due to its smallness in the case

$$E \gg \mu \cdot (k \cdot T/q). \quad \text{(A3)}$$

Neglecting the „dead layer" [7] $E = V/L$, we find

$$V \gg 0.026 \cdot \mu \cdot L. \quad \text{(A4)}$$

It follows from the table that $\mu \cdot L \leq 3$. Therefore, the diffusion current may be neglected if the applied bias voltage is

$$V \gg 0.078\,\text{V}. \quad \text{(A5)}$$

The bias voltages used in [1] were 200 and 400 V.

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Conflict of interest

The authors declare that they have no conflict of interest.

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