Spectral analysis of the photoconductivity for characterization of CdTe и CdZnTe detectors

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Abstract. The results of the application of optical methods are considered: spectral analysis of photoconductivity in the range 400–1800 nm and field measurements of stationar photoconductivity to study the bulk and surface characteristics of CdTe and CdZnTe gamma-ray detectors. The studies of the photoresponse of the samples were carried out in different irradiation modes: modulated at a frequency of 25 Hz and a constant light flux. The measurements were carried out at room temperature on domestic and foreign materials of detector quality. Using the spectral photoconductivity method, the parameters of deep levels, which affect the detector properties, have been estimated in the studied materials. Based on the calculations of the field dependences of the photoconductivity, the volume and surface parameters of the capture and recombination of non-equilibrium carriers in the investigated detectors were determined. The results of calculating the transport characteristics of charge transfer by electrons µτ in detectors are compared with similar parameters measured using the traditional method of irradiating the detector with alpha particles. To measure the band gap in CdTe and CdZnTe at room temperature the method was modified for calculating ΔEg. The possibility of monitoring the Zn content in CdZnTe detectors using the spectral photoconductivity method is shown.

1. Introduction
CdTe (CdZnTe) detectors possessing the high registration efficiency in wide energy range, well spectrometric features and manufacturability take up individual place among semiconducting waterless cooling detectors of X- and γ- radiation. For the purposes of the CdTe (CdZnTe) materials fundamental properties researches the optical methods based on the effects of photoluminescence, IR transmission etc. are widely used as well as for quality control in fabrication process [1]. For the features research the method based on the photoconductivity effect is applied also. Parameter µτ being nonequilibrium carrier mobility multiplication by lifetime is one of the other basic parameters defining the main device features. Along with traditional way of µτ finding, the standing photoconductivity measurement is powerfull tool of material transmission features studying [2]. Presence and concentration of the impurity centers in SC material may be detected and measured with the spectrum distribution of impurity photoconductivity. Analysis of spectrum distribution of impurity photoconductivity as well as photoluminescence and deep-level current relaxation spectroscopy maybe used also for studying nature and features of deep centers [3]. Optical methods of IR radiation absorption and photoluminescence were used for finding the correlation results and quality of CdTe (CdZnTe) detectors [4, 5]. For the same purposes the method of spectrum photoconductivity may be
used also. Due to a little depth of penetration of optical radiation inside material a surface carrier recombination and estimation of a surface quality of contacts when developing etching technique or passivation treatment of the surfaces may be studied [6]. One more important task in detector manufacturing chain is a control of Zn concentration in the CdZnTe crystals with a finding the value of the forbidden gap. Using a spectrum self-photoconductivity seems to be helpful for this purpose. Taking into account a wide scatter of the forbidden gaps values experimentally measured by different ways for CdTe и CdZnTe crystals it looks useful to compare them and the results obtained. Spectrometer setup for the materials parameters research using optical excitation of the nonequilibrium carriers was used for all pointed purposes.

2. Technique for the photoconductivity spectral characteristics measurement

The spectral photoconductivity of the CdTe and CdZnTe samples was measured at room temperature in the wave length range 400–1800 nm. The spectrometric setup included: source of radiation based on a 100 W power halogen tube; monochromator MDR-41; focusing optics; cryostat with sample holding system inside; measuring system; power supply and control systems. The experimental setup had two modes of operation: photocurrent measurement with pulsed or continuous irradiation of the samples. In the first mode, the light beam was bunched by a mechanical chopper at the 25 Hz frequency. The pulsed operation mode reduced the noise and interference, as well as dark current component in output signal. Experimental setup is shown in figure 1. Setup could work at temperatures close to the liquid nitrogen temperatures but all measurements presented further were carried out at room temperature. A negative voltage was applied to the irradiated electrodes. This mode is the most favorable from the point of view of the transfer of electronic current. The electrodes were half transparent for the incoming radiation (the thickness did not exceed 1000 Å).

![Figure 1. Block scheme of the spectrometric setup: 1 – source of radiation, 2 – block of light filters, 3 – chopper, 4 – monochromator, 5 – cryostat, 6 – sample, 7 – lock-in, 8 – voltage source, 9 – controller, 10 – ADC, 11 – PC.](image-url)
The dependences of photoconductivity on voltage can also be used for determination of the transport parameter in the volume \( \mu \tau \) for electrons. For the model of irradiation of a sample with a thickness \( d \) through the front contact, we can write the following expression [8] for the photocurrent density \( j \), assuming a uniform field \( E \), one can write

\[
j = eF \mu \tau E \left\{ 1 - \frac{\mu \tau E}{d} \left( 1 - \exp \left( - \frac{d}{\mu \tau E} \right) \right) \right\},
\]

(1)

where \( F \) is carrier generation rate under the influence of the optical power of light.

The expression is written for the case of uniform photoelectric generation of carriers in the sample volume \( F = \text{const} \) in a simplified form for one type of carriers. It is assumed also, there is no reflection of light upon absorption of light. In CdTe and CdZnTe samples the electron mobility is an order of magnitude higher than the hole mobility, and in the general case measured electronic current. The hole current is usually small (it can be measured by applying the corresponding polarity to the irradiated electrode upon excitation of carriers near contact). For a weak field \( \mu \tau E \ll d \), expression (1) becomes the simple expression

\[
j = eF \mu \tau E.
\]

(2)

For the mode of measuring modulated photocurrent to change the conductivity \( \Delta \sigma \) sample can be written [9], when the dark current can be neglected, one can write

\[
\Delta \sigma = \frac{\Delta U (R_L + R)^2}{U R_L R^2},
\]

(3)

where \( \Delta U \) is the load voltage drop, \( R_L \) and \( R \) are the load resistance and dark sample resistance respectively. For high-resistance CdTe and CdZnTe samples, the load resistance \( R_L \ll R \), resistance associated with the dark current, so expression (3) is simplified

\[
\Delta \sigma = \frac{\Delta U}{U R_L}.
\]

(4)

3. The samples

CdTe and Cd\(_{0.9}\)Zn\(_{0.1}\)Te samples were taken from various manufacturers: JSC "Giredmet", JSC "Crystals Nord" (Russia), "Redlen Technologies Inc." (Canada) and "Acrorad" (Japan). The products of these firms, with on the one hand, it is available on the world and Russian markets and, on the other hand, has either outstanding technical characteristics, or prospects to achieve them. Crystals CdZnTe were grown by the THM zone melting method (Redlen) and a modified by the Bridgman method at high pressure ("Crystals Nord"). CdTe crystals were grown by the THM zone melting method ("Acrorad") and by the Bridgman method at high pressure (JSC "Giredmet"). Sample numbers and their geometric dimensions are presented in tables 1–3. The Zn content in the samples was about 10%. Samples, produced by Crystals Nord, Redlen, Acrorad and JSC Giredmet, had the MSM structure with formed Au or Pt (on Acrorad detectors) contacts. When necessary, the obtained samples were processed grinding, polishing and chemical treatment. On CdTe samples made from bars, grown in JSC "Giredmet", contacts were created by chemical deposition of gold from chloroauric acid. Transport characteristics of charge carriers (carrier mobility \( \mu \) multiplication by lifetime \( \tau \) in the detectors were estimated using the results of measuring the efficiency charge collection CCE (charge collection efficiency) when irradiating planar detectors short-range alpha particles of the \(^{239}\text{Pu}\) source. The \( \mu \tau \) values were calculated from the Hecht equation [10] taking into account the ballistic amplitude deficit that occurs at low electric fields [11]. When measuring dark currents of samples a Keithley 4785 picomammeter was used. Sample resistivity was calculated from the current-voltage characteristics (VAC) at room temperature. Measurement of the electrical conductivity of the measured CdZnTe samples showed that the specific resistance of detectors made of materials from Redlen Technologies Inc., is in the range \((2–6) \times 10^{10} \) Ohm·cm. This range corresponds to the achieved modern world level. Other electrophysical characteristics of the samples by Redlen such as the \( \mu \tau \) parameter were
reproducible and stable despite the fact that the samples were made from crystals of various ingots. All samples were compared by current density at an electric field equal to \( E = 600 \text{ V/cm} \). Current density on samples Redlen was 2–3 nA/cm\(^2\). Samples of CdTe and CdZnTe from other manufacturers had current densities by 1–3 orders of magnitude worse. Note also that the tested samples of CdZnTe "Crystals Nord" had small dimensions and a sufficiently high level of leakage currents, which can also be associated with surface currents. The current density on CdTe samples by Acrorad corresponds to measured resistivity \( 2 \times 10^{10} \text{ Ohm}\cdot\text{cm} \), which corresponds to the world level detector building. The indicated difference in the values of the resistivity of CdTe and CdZnTe is more than an order of magnitude related to the different band gap, which is also was confirmed by the measured intrinsic absorption band in determining photoconductivity. The leakage currents on the measured CdTe samples of JSC "Giredmet" had too large, which limits their use for solving most tasks on spectrometry of gamma radiation.

The I–V characteristics of all the studied CdTe samples in total had a quasi-ohm behavior. On the contrary, the Schottky-shaped I–V characteristic of CdZnTe samples with gold contacts indicates that the conductivity type of these samples is closer to the n-type. Creature reproducible barrier contacts on semi-insulating CdZnTe detectors with the minimum surface area and volume charges near the surface is quite a difficult task. Measurements of the collection efficiency of carriers on detectors have confirmed that transport properties of electrons on CdZnTe detectors are much better than on samples CdTe. The available samples of CdZnTe from Redlen were characterized by the index \((\mu\tau)_{e} \) for electrons in the range \((4–7) \times 10^{3} \text{ cm}^{2}/\text{V} \cdot \text{s} \). On these samples, it was difficult to get enough good hole signal for determining the parameter \((\mu\tau)_{h} \) for holes. For the purposes of our experiment were selected two samples of CdZnTe by Redlen with different indicators parameter \((\mu\tau)_{e} \). Satisfactory results in charge collection efficiency showed samples made from CdTe and CdZnTe crystals created at JSC "Giredmet" and JSC Crystals Nord. Samples of JSC "Giredmet" had a parameter \((\mu\tau)_{e} \) for electrons equal to \((3–9) \times 10^{4} \text{ cm}^{2}/\text{V} \cdot \text{s} \), samples of JSC "Crystals Nord" \((1–4) \times 10^{5} \text{ cm}^{2}/\text{V} \cdot \text{s} \). In table 1 the measured basic electrophysical properties used for spectral studies by optical methods of CdTe and CdZnTe samples are presented.

### Table 1. Electrophysical properties of CdTe \& CdZnTe samples.

| \(N_e\) | Manufacturer      | Material | Size, \(\text{mm}^3\) | \((\mu\tau)_e\), \(\text{cm}^2/\text{V}\cdot\text{s}\) | \((\mu\tau)_h\), \(\text{cm}^2/\text{V}\cdot\text{s}\) | \(\rho\), \(\text{Ohm}\cdot\text{cm}\) |
|--------|-------------------|---------|----------------------|---------------------------------|---------------------------------|------------------|
| 10–16  | «Giredmet»        | CdTe    | \(4.9\times4.9\times1.9\) | \(3.9\times10 \) \(^{-4}\) | \(3.5\times10 \) \(^{-5}\) | \(2.8\times10 \) \(^{4}\) |
| 14–13  | «Giredmet»        | CdTe    | \(4.2\times4.2\times1.1\) | \(7.7\times10 \) \(^{-4}\) | \(7.2\times10 \) \(^{-5}\) | \(6.9\times10 \) \(^{4}\) |
| 903–37 | «Acrorad»         | CdTe    | \(5\times10\times3\)   | \(1.8\times10 \) \(^{-3}\) | \(1.2\times10 \) \(^{-4}\) | \(2.8\times10 \) \(^{6}\) |
| 5      | «Crystals Nord»   | CdZnTe  | \(1.2\times3.7\times2.2\) | \(1.3\times10 \) \(^{-5}\) | -                              | \(8.1\times10 \) \(^{9}\) |
| 27078  | «Redlen»          | CdZnTe  | \(10\times10\times5\)   | \(7\times10 \) \(^{-3}\)  | \(1\times10 \) \(^{-4}\)    | \(3.4\times10 \) \(^{10}\) |
| 28288  | «Redlen»          | CdZnTe  | \(10\times10\times5\)   | \(2\times10 \) \(^{-3}\)  | \(1\times10 \) \(^{-4}\)    | \(3.8\times10 \) \(^{10}\) |

Samples were processed grinding, polishing. Drift mobilities of both electrons and holes on CdTe Acorrad and CdZnTe Redlen samples had the expected values and were in line with the data available in papers. On the other hand, the values of the drift mobility of the CdTe and CdZnTe samples, manufactured by JSC "Giredmet" and JSC "Crystals Nord" were 20–25% less, which indicated the existence in these samples of a large number of shallow-lying traps.

4. **Experimental results on measuring the spectral characteristics of the photoconductivity**

For all 6 samples of CdTe and CdZnTe, the spectral photoconductivity was measured at room temperature in the 400–1800 nm range of wave length. As a rule the bunched light beam was used for
the photocurrent measurements; for some samples the photocurrent was measured on irradiating with continuous light. Photocurrent vs wave length for the sample CdTe Acorad № 903-37 irradiated with the bunched light is presented on figure 2. For some samples, for example CdZnTe № 28288 sample (see figure 3), measurements were done in a voltages range 20–70 V.

Figure 2. The spectral photoconductivity ($T = 300$ K) for CdTe Acorad sample № 903-37 at voltage $U = 30$ V.

Figure 3. The spectral photoconductivity ($T = 300$ K) for CdZnTe sample № 28288: $1 – U = 40$ V, $2 – U = 70$ V.

The general features of the photoconductivity spectra should be noted. Dependencies have three regions: shortwave region (A) in the range 400–750 nm, region intrinsic absorption (B) and the third region (C) of impurity absorption 900–1500 nm. The intrinsic absorption region had a different location in the spectra in depending on the material – for CdTe it was in the range of 820–890 nm, while for CdZnTe – 780–840 nm. Wide peak of photoconductivity (region A) with a maximum of 600–700 nm can be associated with the presence of compounds directly adjacent to the contact, mainly oxide compounds. To provide more reliable information about separate research is needed in this area. Long wave length region C spectra is associated with deep and shallow levels that exist inside the forbidden detector zones. Some characteristics of the spectra are presented in table 2: data on the position of the maxima intrinsic absorption and impurity absorption of the photospectra, as well
as the values equal to the ratio of the intensities of these two bands. Apparently, this characteristic should also characterize the concentration of deep carrier trapping centers in material.

Table 2. Characteristics of the spectra for CdTe и CdZnTe samples.

| №  | Region B      | Region C     | $I_c/I_B$ |
|----|---------------|--------------|-----------|
|    | $\lambda_{\text{max}}$, nm | FWHM, % | Range, nm | $\lambda_{\text{max}}$, nm |
| 10–16 | 872 | 4.47 | 1030–1320 | 1150 | 3.2·10^{-3} |
| 14–13 | 861.5 | 4.35 | 1000–1400 | 1180 | 8.6·10^{-3} |
| 903–37 | 862 | 0.94 | - | - |
| 5 | 811.5 | 3.25 | 1000–1600 | 1175 | 2.8·10^{-2} |
| 27078 | 818 | 2.84 | 1000–1350 | - | 5.8·10^{-4} |
| 28288 | 810 | 1.97 ($U = 20$ V) | 6.5 ($U = 70$ V) | 1000–1140 | - |

Results of spectral analysis of impurity photoconductivity in the studied samples show the presence of a spectral region in which an increased photosensitivity in the wavelength range 1000–1400 nm for CdTe and 1000–1600 nm for CdZnTe. For CdTe, these are detectors manufactured by JSC "Giredmet" (№ 10–16 and № 14–13 samples). For CdZnTe are detectors manufactured by Crystals Nord. Figures 4–7 shows spectral dependences of the photocurrent in the region of impurity absorption for these samples.

In [5], various compositions of etchants for the surface of CdZnTe detectors were studied. In the ratio of intensities was used as one of the evaluation criteria low-temperature photoluminescence observed in different bands: a) bound exciton to neutral donors $D^0X$; b) bound exciton to neutral acceptors donors $A^0X$; c) peak of recombination of donor-acceptor pairs of DAP; and d) peak of defective bands 1.42–1.57 eV. As a result, the correlation of the coefficients was established $k = I(D^0X)/I(\text{def})$ with detector quality.

The ratio of the intensities of the impurity band (C) and the band associated with intrinsic absorption $k = I(C)/I(B)$ correlates quite well with the parameters ($\mu r_e$) for electrons and with an energy resolution of the studied samples. This allows assume that the absorption of light in this region occurs, including with the participation levels responsible for the capture of carriers (primarily electrons). Samples № 10–16; № 14–13 and № 5, the transport characteristics ($\mu r_e$) of which are the worst among investigated, show (see figure 4–6) on the spectra of photoconductivity signals in the region 0.8–1.2 keV. These signals can be interpreted as transitions involving deep levels. Considering that they appear in the spectral dependences of different manufacturers, this gives reason to interpret them as one of the types of structural defects.

It looks interesting that undoped high-resistance and low-resistance CdTe samples had similar spectra of impurity photoconductivity in the range of 0.95–1.3 eV [12]. Moreover, on In and Cl doped high-resistance p-type CdTe samples there were no similar signals. The authors interpreted these changes in the spectra due to the reaction of shallow donor levels associated with In and Cl with the structural a defect in the middle of the ZP with an energy $E_r + 0.95$ eV. In [3], on Bi-doped CdTe samples, strong signals were measured with photoconductivity spectra in the range of 1.0–1.4 eV. Based data from low-temperature PL and PICT, the results were interpreted by the formation deep level with an energy of $E_r + 0.71$ eV, associated with a donor complex based on Bi and cation vacancy. However, the authors also did not exclude that this level could be associated with some structural defect, such as the Te$_{cd}$ antising defect.
Figure 4. The spectral photoconductivity ($T = 300$ K) for CdZnTe «Crystals Nord» sample №5 at voltage $U = 50$ V.

Figure 5. The spectral photoconductivity ($T = 300$ K) for CdTe «Giredmet» sample №14–13 at voltage $U = 30$ V.

Figure 6. The spectral photoconductivity ($T = 300$ K) for CdTe «Giredmet» sample №10–16 at voltage $U = 30$ V.
Figure 7. The spectral photoconductivity \((T = 300 \text{ K})\) for CdZnTe Redlen sample № 27078 at voltage \(U = 40 \text{ V}\).

In [13], considering the compensation processes in CdTe and CdZnTe crystals on based on the PICT) and P-DLTS methods, participation in these processes was postulated antisite defect Te\(_{Cd}\) donor type with energy \(E_v + 0.75 \text{ eV}\) (center H1). It is known that for the production of semi-insulating detectors CdTe and CdZnTe the technologies for compensation of donor and acceptor impurities with the participation of deep acceptor levels, such as the cation vacancy of V\(_{Cd}\) and antisite defect Te\(_{Cd}\) are used. The self-compensation scheme involves the so-called A-center – a complex consisting of a doubly charged acceptor center V\(_{Cd}\)^2+ and shallow donor impurity.

In [14], deep centers \(E_c - 0.55 \text{ eV}\) were studied in CdZnTe; \(E_c - 0.70 \text{ eV}\); \(E_c - 1.09 \text{ eV}\) by methods photoluminescence, while it turned out that the centers \(E_c - 0.55 \text{ eV}\) correlate with photoconductivity, and photoconductivity and charge collection efficiency data correlate with the center \(E_c - 0.70 \text{ eV}\).

Our studies of deep levels, carried out by the methods of PICT on other samples of CdTe and CdZnTe allows us to state that in all measured CdZnTe samples hole centers with an energy \(E_v + (0.91 - 0.94) \cdot 10 \text{ eV}\) and a capture cross section of \(10^{-9} - 10^{-11} \text{ cm}^2\) were observed. In the worst sample, in terms of electronic transport characteristics, good a peak with energies \(E_c - 0.77 \text{ eV}\) and a capture cross section of \(10^{-12} \text{ cm}^2\) was distinguished, which can be correlated with center H1. Traps with energy \(E_v + (0.44 - 0.46) \cdot 10 \text{ eV}\) with a capture cross section of \(10^{-12} - 10^{-14} \text{ cm}^2\), which were presumably attributed to cationic vacancies V\(_{Cd}\)^2+ in the charged complex.

In general, the measured signals in the impurity photoconductivity spectra in the range 0.8–1.2 keV can be interpreted as obtained by optical excitation electrons with the participation of several centers and resulting in impurity hole and electronic photoconductivity. In the first case, photoconductivity can appear in as a result of electron transitions from the valence band to the levels \(E_v + (0.91 - 0.94) \cdot 10 \text{ eV}\) and \(E_v + (0.44 - 0.46) \cdot 10 \text{ eV}\). In the second case, photoconductivity arises as a result of transitions of electrons from levels \(E_v + (0.44 - 0.46) \cdot 10 \text{ eV}\) into the conduction band.

The intrinsic absorption maxima correspond to energies of 1.51–1.53 eV for the studied CdZnTe samples and 1.42–1.43 eV – for the CdTe samples. Overall, these results corresponds to the expected, considering also that the positions of the maxima of the intrinsic absorption also depends on the absorption of photons and the recombination of carriers in near-surface detector.

5. **Forbidden area width of the samples material estimation**

Determination of the Zn content in Cd\(_{1-x}\)Zn\(_x\)Te samples, as is known, it is possible to determine by direct methods of X-ray diffraction or infrared spectra absorption. Methods for determining the composition of crystals are also widely used based on from the value of the band gap \(\Delta E_g\) according to the existing dependences \(\Delta E_g(x)\). For For this, at low temperatures, photoluminescence is usually used with the definition the energies of the bound D0X exciton or free exciton [15]. At room temperature to measure the band gap \(\Delta E_g\) can be used several methods: photoluminescence [16], photoreflection, optical transmission [17], [18] and photoconductivity [19]. In this case, there is a large scatter of the
measured band gap widths of CdTe crystals from 1.39 eV to 1.54 eV and Cd$_{1-x}$Zn$_x$Te ($x = 0.1$) from 1.51 eV to 1.58 eV.

Determination of the forbidden gap $\Delta E_g$ using photoconductivity is usually lead along the characteristic points of the long-wavelength edge of the intrinsic conductivity spectrum: at point where half photosensitivity is achieved. However, as can be seen on figure 3, the position of the photoconductivity peak of the CdZnTe sample № 28288 strongly depends on voltage applied to the sample. The energy of the zone $\Delta E_g$, determined in accordance with this way to be underestimated. It can be assumed that the course of the dependence of the curve photoconductivity at the red absorption edge is associated with the excitation of centers, the energy position of which is at the edge of the zones associated with free and bound excitons and donor-acceptor pairs. When absorption of photons with energy $E < \Delta E_g$, the formation of electron-hole pairs can occur already over the volume inside the sample.

Methodologically, the value of $\Delta E_g$ must be determined on the decline shortwave spectral region. The decline in the curve in this area is associated with the growth coefficient of absorption of photons, while on the surface of the detector (under the electrode) the probability of capture of excited carriers by various defects is much higher, than in volume. Photosensitivity of the sample upon excitation of nonequilibrium carriers photons with energy $E = \Delta E_g$ should remain relatively low, even taking into account inhomogeneity of the crystal structure and the likelihood of thermal overshoot. In work the determination of $\Delta E_g$ in the short-wavelength region of the spectrum is carried out according to the linear section of the decay of the spectral characteristic at the point of its inflection before crossing with horizontal section as shown in figure 8.

![Figure 8. The determination of the $\Delta E_g$ value on the decline of the short-wavelength spectral region. The CdTe «Acorad» sample № 903-37 at voltage $U = 30$ V.](image)

Table 3 shows the calculated values of the band gap in the investigated samples CdTe and Cd$_{0.9}$Zn$_{0.1}$Te. Values without brackets correspond to measurements spectral photoconductivity using a synchronous detector. As seen from table 3, the use of a synchronous detector reduces the results of calculations of $\Delta E_g$ by 0.01–0.02 eV. On average, for CdTe from two manufacturers of single crystals, the zone was 1.472. Similar results for Cd$_{0.9}$Zn$_{0.1}$Te amounted to 1.535 eV. The obtained results on $\Delta E_g$ at room temperature for CdTe and Cd$_{0.9}$Zn$_{0.1}$Te are good correspond to the literature data, for example, those indicated in [18]: 1.47–1.48 eV for CdTe and 1.52–1.53 eV for Cd$_{0.9}$Zn$_{0.1}$Te and 1.470 eV for CdTe indicated in [17].

Assuming a linear approximation, the determination of the Zn content in the Cd$_{1-x}$Zn$_x$Te can be estimated according to the relation

$$\Delta E_g(x) = 1.472 + 0.63x.$$ (5)
### Table 3. The band gap in the studied CdTe and CdZnTe samples.

| №  | Material       | $\Delta E_g$, eV (300K) |
|----|----------------|-------------------------|
| 10–16 | CdTe         | 1.465                   |
| 14–13  | CdTe         | 1.481 (1.492)           |
| 903-37 | CdTe         | 1.472                   |
| 5       | Cd$_{0.9}$Zn$_{0.1}$Te | 1.5285 (1.548)         |
| 27078  | Cd$_{0.9}$Zn$_{0.1}$Te | 1.54 (1.56)            |
| 28288  | Cd$_{0.9}$Zn$_{0.1}$Te | (1.558)                 |

6. The surface recombination of carriers

In order to study the surface recombination of carriers in CdTe and Cd$_{0.9}$Zn$_{0.1}$Te detectors, they were irradiated with light of greater energy within the energy zone $\Delta E_g$. Due to the shallow penetration depth of optical radiation, recombination of carriers at low electric fields will occur on the surface of the detector. To measure the dependence of photoconductivity on voltage, we used a similar model and expression (1). Expression for photocurrent $I$ upon excitation of carriers on the contact will look like this [20]

$$I = I_0 \mu \tau E \frac{d}{d} \left( \frac{1}{1 + \left( \frac{s}{\mu \tau E} \right)} \right) \left( 1 - \exp \left( - \frac{d}{\mu \tau E} \right) \right),$$

where $s$ is the surface recombination velocity and where $I_0$ is the saturation current. In figure 9–10, we show the dependences of the photocurrent on the applied voltage for some samples upon excitation by photons with energies higher than the forbidden energy material zones.

![Figure 9. Photocurrent of the CdZnTe Redlen sample №27078 vs applied voltage. The contact illuminated with 700 nm light.](image)

When fitting the experimental dependence of the photocurrent of the CdZnTe Redlen №27078 (figure 9) model curve (1) was determined by the transport transfer parameter $(\mu \tau)_e$ equal to $2.4 \cdot 10^{-3}$ cm$^2$/V at a saturation current of 1400 nA. The value obtained in this way $(\mu \tau)_e$ is sufficiently close to the analogous parameter obtained from the Hecht relation.

As can be seen from figure 10, the dependence of the photocurrent on the CdTe sample Acrorad №903-37 at small electric fields had the shape of a "heel", indicating the presence of surface recombination. The dependence of the photocurrent on the sample had a similar form CdTe Giredmet №1413. Such dependences appear when illuminated by photons with energy exceeding the band gap. To process the dependence of the photocurrent on the voltage, equation (6) was used. When fitted with the corresponding model function, you can determine the velocities of surface recombination, which on the CdTe sample №1413 by Giredmet was $8 \cdot 10^{-4}$ cm/s and on the Acrorad sample №903-37 – $5 \cdot 10^{-5}$ cm/s. Thus, samples whose transport characteristics can be diametrically differ, can be compared by the quality of surface treatment. In this case, we see that due to the worst surface
treatment technology (polishing quality, etching) sample CdTe № 4–13 from JSC ’Giredmet’ had the worst values of the rate surface recombination in comparison with the sample № 903-37 by Acrorad.

Figure 10. Photocurrent of the CdTe Acrorad sample № 903-37 vs applied voltage. The contact illuminated with 800 nm light.

7. Conclusions
Spectral photoconductivity and field measurements of stationary photoconductivity is a powerful tool for investigating bulk and surface characteristics of CdTe and CdZnTe gamma-ray detectors. Was shown, that, using the methods of impurity spectral photoconductivity, one can analyze deep levels in high-resistance detectors and investigate the correlation with electrophysical characteristics of detectors, primarily with transport media transfer options. Such an analysis for the selected samples of CdTe and Cd_{0.9}Zn_{0.1}Te domestic and foreign manufacturers (Giredmet, Crystals Nord, Redlen and Acrorad) was made and a good correlation of the spectral analysis results with characteristics of the detectors. Deep-level measurements in CdTe and Cd_{0.9}Zn_{0.1}Te were interpreted within the framework of the available data on the PICT, including made by us earlier. The field dependences of the photoconductivity were calculated and determined for they are based on the bulk and surface parameters of capture and recombination of nonequilibrium carriers. Thus, the parameter (\(\mu\tau\)) on the CdZnTe Redlen sample № 27078 was 2.4 \times 10^{-3} \text{cm}^2/\text{s}, and the surface recombination velocities on the Giredmet and Acrorad CdTe samples were 8 \times 10^{-4} \text{cm/s} and 5 \times 10^{-5} \text{cm/s}, respectively. Using the results of such calculations you can evaluate the quality of contacts and work out the technology of etching the surface, its passivation. To measure the band gap in CdTe and CdZnTe at room temperature using spectral intrinsic photoconductivity methods, the method was modified for calculating \(\Delta E_p\). The measurements have shown a high degree of agreement of obtained values of \(\Delta E_p\) with literature data measured by other different ways. It was also shown that using this method it is possible to carry out reliable control of the Zn content in Cd_{1-x}Zn_xTe crystals by the ratio.

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